Review of the Basics of Modular Multilevel Converter Using 120-Degree Discontinuous PWM

Kazunobu Oi,
Yugo Tadano

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Abstract

The modular multilevel converter consists of combination of modules. Each module is composed of multiple minimum-unit converters called "cells" in a cascade connection. This modular multilevel converter can easily realize the generation of high voltage output without using a transformer and reduction of harmonics and switching losses. There is, however, an issue of substantial conduction loss. The converter devised comes in a configuration where the upper arm modules are replaced by high-voltage Insulated Gate Bipolar Transistors (IGBTs). In this way, the number of cells can be reduced by half. By adopting a 120-degree discontinuous PWM, conduction loss can be reduced by diverting a current through a high-voltage IGBT in 1/3 the period. In the same section, a cell capacitor voltage is controlled to a constant level by the effect of a circulating current. An increase in losses is suppressed by the switching of a high-voltage IGBT at current zero. By simulation, we confirmed that losses can be reduced by 30% as compared with conventional circuiting. We completed the verification on the operational principle and basic performance based on the miniature model experiment.

1 Preface

The Modular Multilevel Converter (MMC) [1][2] is composed of converter arms where multiple chopper cells are arranged in a cascade connection. This type of converter features a high voltage circuit that can be easily established by increasing the number of connecting cells. In addition, since the output voltage can be established in multi-level mode, flow-out harmonics can be minimized. When the switching timing of respective cells is shifted, the switching frequency of a single unit can be lowered and the equivalent switching frequency can be raised. Thus, the MMC features switching losses that can be reduced [3].

A configuration where two sets of upper and lower MMCs in star connection (DSCC: Double-Star Chopper-Cells) [4] is capable of DC-AC mutual conversion. In this case, however, it requires an increase of the number of switching elements or chopper cells for higher voltage, therefore, the number of switching element through which the current flows increases. This creates an issue of an increase of conduction loss. As a method to reduce conduction losses, a cell capacitor voltage raises and the number of cell units decrease. This method, however, invites an issue that switching loss can greatly increase when high-voltage IGBTs (insulated gate bipolar transistors) of 3 kV or higher class are adopted.

This paper introduces our invention of an advanced MMC configuration. In order to resolve these issues, we replaced the upper-side converter arms with high-voltage IGBTs by applying a 120-degree discontinuous PWM. First, we will introduce the proposed circuit configuration and its operational principle, and then the circulating current required for chopper cell voltage control is derived. We will then confirm the proposed circuit will work normally and it will reduce the conduction loss.

We will verify these points by the results of a miniature model experiment and simulation.

2 Configuration and Operational Principle of the Proposed Circuit

Fig. 1 shows the Main Circuit Configuration of the MMC. The chopper cell consists of DC capacitors and two low-voltage IGBTs of 1700V class or lower. The lower arm is configured where a module with multiple chopper cells in a cascade connection connects with a buffer reactor L_B. The upper arm has a high-voltage IGBT and a snubber capacitor is connected in parallel. The number of series connections of the lower arm chopper cells and the upper arm high-voltage IGBT is adjusted according to the withstand voltage specified. In **Fig. 1**, since 4 chopper cells are used, the phase voltage falls on Level 5.

Fig. 2 shows waveforms of an output phase voltage. Since 120-degree discontinuous PWM[5] is applied to the proposed circuit, one of the output phase voltages becomes equal to V_{DC}. In one period in Phase U, the section is defined as (a) where v'_U is not higher than V_{DC}, (c) where it is equal to V_{DC}, and Sections (b) and (d) are inserted between (a) and (c). In this layout, high-voltage IGBT ON/OFF switchover in the upper arm and module control in the lower arm are performed in order to actuate the proposed circuit.

Fig. 3 shows a current path in each section. First, the high-voltage IGBT is OFF in Section (a). An AC output current is generated from the lower arm. Next, in Section (b), the high-voltage IGBT is turned ON but the snubber capacitor is short-circuited if the same situation continues. Accordingly, a current output larger than the AC output current is generated from the lower arm before the high-voltage IGBT is ON. By taking this action, the snubber capacitor is discharged in advance and the high-voltage IGBT can be turned ON without causing short-circuiting. In Section (c), the high-voltage IGBT is ON. In this case, the AC output current does not pass through the lower arm where multiple cells are connected but passes through the upper arm where a few high-voltage IGBTs are connected. For this reason, conduction losses can be lowered. A circulating current is led to the lower arm module from the DC bus via the high-voltage IGBT so that cell capacitor voltage is controlled in the lower arm. Lastly, in Section (d), the current bypasses the snubber capacitor even if the high-

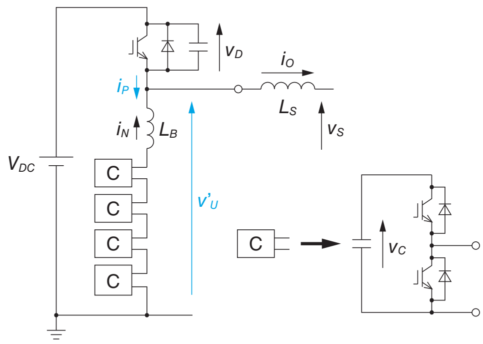

Fig. 1 Main Circuit Configuration of the MMC

A configuration for only one phase is shown. The upper-arm cell module is replaced with a high-voltage IGBT having a snubber capacitor.

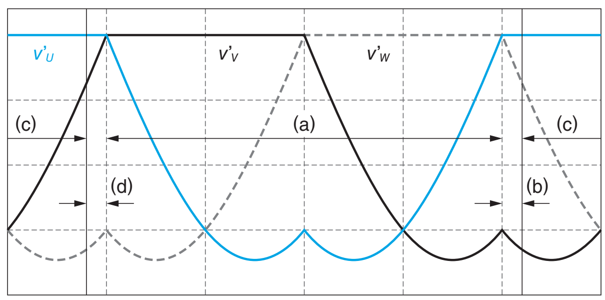

Fig. 2 Waveforms of Output Phase Voltage

The 120-degree discontinuous PWM is applied so that ON/OFF switching of upper-arm high-voltage IGBT can be performed in each section.

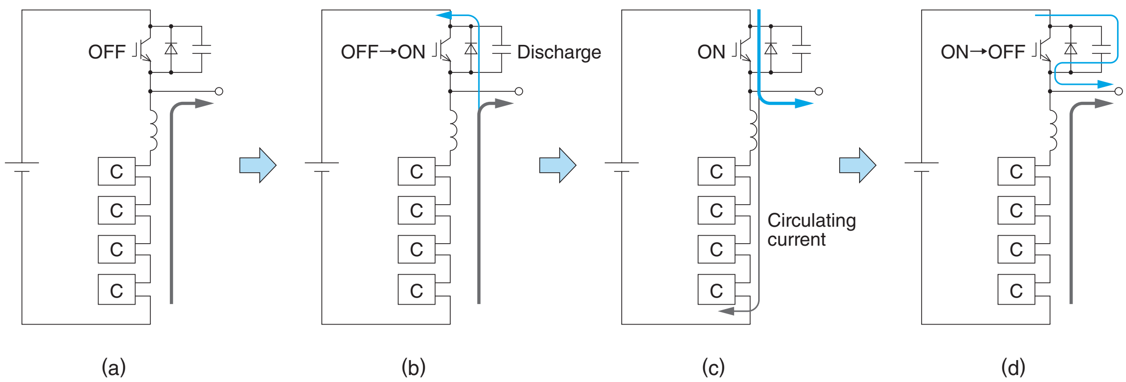

Fig. 3 Current Path in Each Section

In Section (b), the snubber capacitor is discharged from the lower arm. In Section (c), conduction loss is reduced by generating a current output from the upper arm. Cell capacitor voltage is regulated with the aid of a circulating current.

voltage IGBT is turned off as it is. Thus, soft switching is established.

By the effects of this circuit operation, switching losses are drastically minimized. This loss issue had been an inherent challenge of high-voltage IGBTs. Another merit is that no voltage surges are generated at the time of switching in the high-voltage IGBTs and it is possible to decrease the number of series connections.

3 Circulating Current for Cell Capacitor Control

In this section, the circulating current is evaluated because it is needed for the cell capacitor voltage control of the proposed circuit. Assuming that the rms value of AC line-to-line voltage is V, AC phase voltage in Phase U is expressed by $v_{SU}=\sqrt{2/3}\,V\cos\omega t$, and AC current in Phase U is expressed by $i_{OU}=\sqrt{2}\,I\cos(\omega t-\phi)$. Then, output voltage v'_U in Phase U after application of 120-degree discontinuous PWM is given by Expression (1) below.

$$v'_U=\begin{cases} V_{DC} & \left(-\dfrac{\pi}{3}<\omega t<\dfrac{\pi}{3}\right)\\ \sqrt{2}V\cos\left(\omega t-\dfrac{\pi}{6}\right)+V_{DC} & \left(-\pi<\omega t<-\dfrac{\pi}{3}\right)\\ \sqrt{2}V\cos\left(\omega t+\dfrac{\pi}{6}\right)+V_{DC} & \left(\dfrac{\pi}{3}<\omega t<\pi\right)\end{cases}\quad\cdots\cdots(1)$$

Where, $0<V<V_{DC}/\sqrt{2}$

All the output power in Section (a) is assumed to be shouldered by the lower-arm cell module. Energy E_a at that time is obtained from Expression (2) below.

$$E_a=\int_{-\pi/\omega}^{-\pi/3\omega} v'_U\, i_{OU}\,dt+\int_{\pi/3\omega}^{\pi/\omega} v'_U\, i_{OU}\,dt$$

$$=\frac{I\cos\phi}{\sqrt{3}\,\omega}\left(2\pi V-3\sqrt{2}V_{DC}\right)\quad\cdots\cdots(2)$$

In Section (c), the circulating current I_C is assumed to be constant. Energy E_c charged by I_C is given by Expression (3) below.

$$E_c=\int_{-\pi/3\omega}^{\pi/3\omega} v'_U\, I_C\,dt=\frac{2\pi I_C V_{DC}}{3\omega}\quad\cdots\cdots(3)$$

Since $E_a+E_c=0$, the circulating current is given by Expression (4) below.

$$I_C=\sqrt{3}I\cos\phi\left(\frac{3}{\pi\sqrt{2}}-\frac{V}{V_{DC}}\right)\quad\cdots\cdots(4)$$

For reference, the circulating current I_{CD} of conventional DSCC type MMC is given be Expression (5) below.

$$I_{CD}=\frac{VI\cos\phi}{\sqrt{3}V_{DC}}\quad\cdots\cdots(5)$$

Unlike the DSCC type, the section where a circulating current can be carried is limited to Section (c) in the proposed circuit. In Section (c), however, power is directly transmitted from DC side to AC side via the high-voltage IGBT and therefore, total losses can be reduced. If the DC voltage is designed to be $V_{DC}=\pi\sqrt{2}\,V/3=1.481V$, the required circulating current can be significantly lowered at any output current and power factor. On the other hand, in the case of DSCC type, the required circulating current is increased in proportion to the output voltage and current amplitude. The proposed circuit can realize a high efficiency if it is applied to system interlinkage, for example, where a voltage at an almost constant amplitude is maintained for a long time.

4 Loss Evaluation by Simulation

In order to verify the effect of conduction loss reduction in the proposed circuit, switching device loss was compared with that of the DSCC type MMC by simulation. Conditions for simulation are that line-to-line voltage is assumed to be 4.4 kV, rated capacity 2 MVA, frequency 50 Hz, 8 cells per arm, and 2 upper-arm high-voltage IGBTs connected in series in the proposed circuit.

Fig. 4 shows result of switching devices loss. For both input and output effective power, conduc-

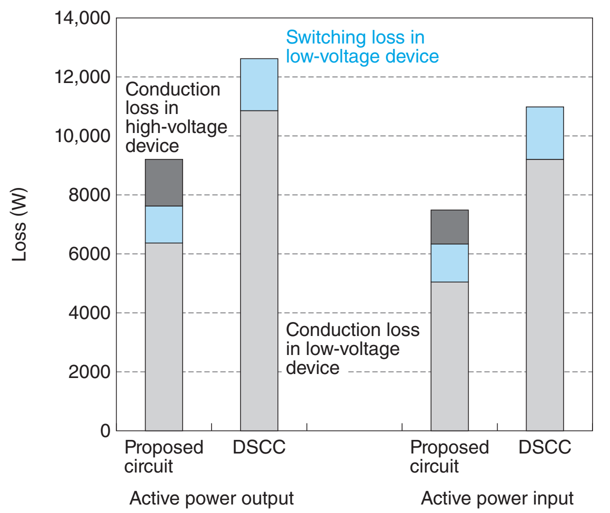

Fig. 4 Result of Switching Devices Loss

Compared with conventional circuits, the proposed circuit can reduce conduction loss. Switching losses in high-voltage switching devices are almost null. As such, soft switching is available with the proposed circuit.

tion losses were greatly decreased in low-voltage devices of the proposed circuit. Switching loss in a high-voltage device was almost zero. This result shows that a reasonable soft switching performance was attained. The difference in total losses is approximately 3.5 kW, which is 0.17% to the equipment capacity. Compared with the DSCC type, the proposed circuit can reduce losses by about 30%.

5 Confirmation of Operational Principle with Miniature Model

In order to examine the performance of the proposed circuit, we conducted a series of testing on a miniature model. Specifications of the miniature model are a line-to-line voltage is 415 V, a rated capacity 15 kVA, and a system frequency 50 Hz. Each arm is composed of 4 cells and the upper arm has a 1200 V IGBT in a single configuration, not in a series connection. Under such conditions, we measured the voltage and current waveforms at each part while the rated reactive power was generated.

Fig. 5 shows the test result waveforms of the miniature model. Before −0.02 seconds, a lagging reactive power is generated. After 0.02 seconds, however, a leading reactive power is generated. The Total Harmonic Distortion (THD) in the AC output current is 4.1% and 3.7%, respectively. In Section (b) that is put in between Section (a) and Section (c), the upper arm current i_{PU} is negative. This suggests that the snubber capacitor is discharged before the high-voltage IGBT is ON. In Section (c), performance of the output current detouring through the upper arm and capacitor charging action by using circulating current were realized. Regarding the cell capacitor voltage, dispersion of maximum and minimum values is very small and stabilized control was secured. Even in the middle of output current changing, its waveform was maintained with a correct sinusoidal curve. As a result of testing with the miniature model, we confirm that the proposed circuit can be operated in a stable manner according to its operational principle.

6 Postscript

This paper introduced a newly proposed circuit of the MMC to which a 120-degree discontinuous PWM is applied. Simulation and miniature model testing were conducted to evaluate the losses in the

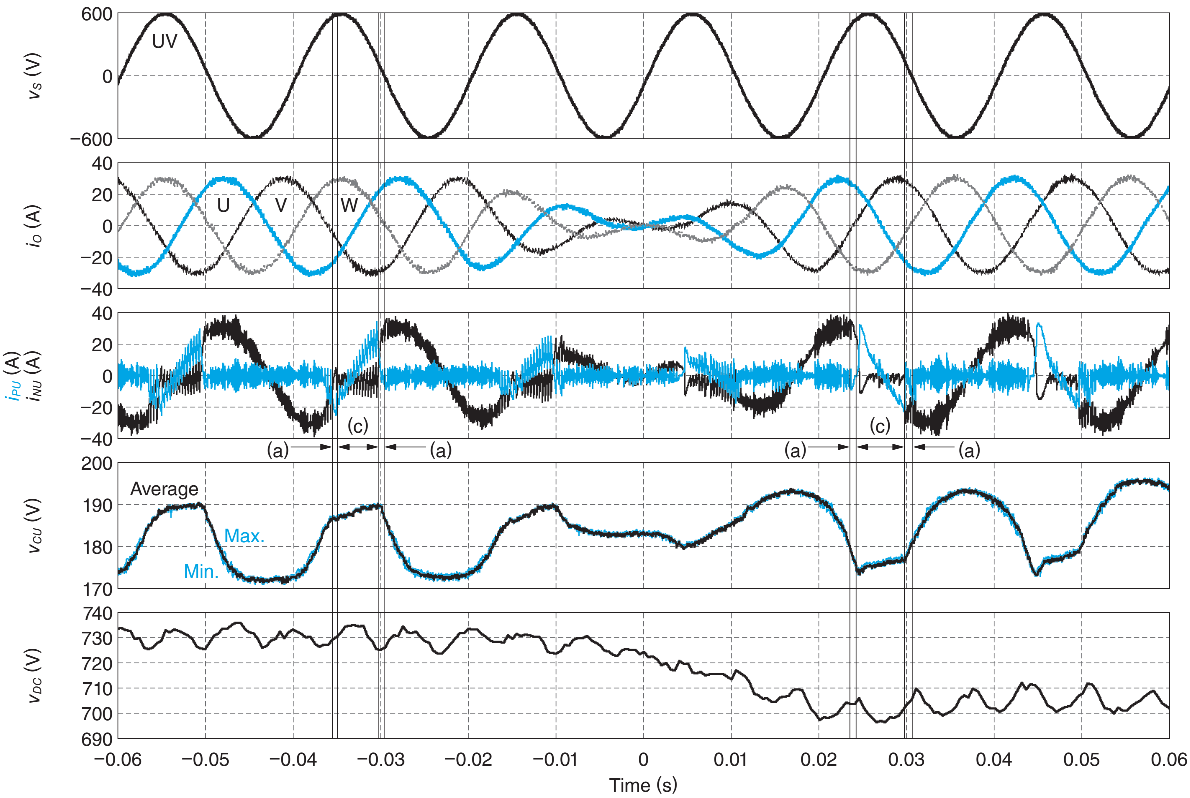

Fig. 5 **Test Result Waveforms of the Miniature Model**

Output current distortion is minimal, cell capacitor voltage control is stable, and circuit operation is just conforming to the principle.

proposed circuit and verify the operational principle. The result shows that the proposed circuit can be operated in a stable manner according to the principle and that a high efficiency can be attained by reduction of conduction losses.

Going forward, we will conduct further evaluation tests for the application of the proposed circuit to actual products. In doing so, we will promote the innovations on a unique circuit and propose suitable control systems.

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