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A Selection Precharge Method for Modular Multilevel Converter

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Abstract

The precharge of the capacitors in sub-modules is essential to the normal operation of the modular multilevel converter. Based on the analysis of the topology and the operation theory of the MMC. This paper analyzed the process of uncontrolled charging method, then explained the reason why the capacitor voltage can't be charged to the desired value. To solve this problem, a selection charging method is proposed and the relative charging process is discussed. By this method, not only the number of sub-modules which needed to be charged at the same time can be reduced, but also the three phase can be charged at the same time. Depend on this method the voltage of capacitor could be rose to the desired value. The feasibility of the proposed strategy is verified by MATLAB/Simulink simulation and experiment results.

***Keywords**: modular multilevel converter, uncontrolled charging method, selection charging method*

1. Introduction

Modular Multilevel Converter (MMC) is a new multilevel converter topology which is first proposed by Marquardt and Lesnicar in 2003 [1]. Compared with the traditional two level or three level topology, MMC is an effective solution to the problem of switching devices to afford large voltage and current in high power applications. Also it has many other excellent performances, such as, lower harmonic content [2-3], easier redundant structure design, higher stability of the system. At present, the researches of MMC mainly focus on modulation strategies [4-5], sub-module balance control strategies [6-7] and circulating current suppressing strategies [8]. However, few researches are done on pre-charge strategies.

At present, pre-charge methods are mainly divided into self-excitation and separate excitation. Control strategies of the latter are simple, but they need additional auxiliary equipment. So they are mainly used in laboratory research. Self-excitation methods rely on the existing circuit without additional voltage source, so they are mainly used in engineering conditions.

The literature [9] presents a separate excitation charging method which charge sub-module one by one by parallel DC power in DC bus side. This method is suitable for both the inverter and the rectifier systems. But with the increase of the number of sub-modules, the capacitor voltage of the sub-modules which have been charged completely may be lower than the desired value. The literature [10] presents a self-excitation method which can charge sub-modules one by one by using AC voltage without using auxiliary voltage. In addition, it reduces the cost and has a good effect in rectifier system which has a few sub-modules. But there are still same problems with the increase of the number of sub-modules, the capacitor voltage of the sub-modules which have been charged completely may be discharged more. To overcome the shortcomings of the method of charging sub-modules one by one, the literature [11] improves the sub-modules' structure by adding four anti-parallel thyristor. This method can charge all sub-modules at the same time. Also the charging time is short and control strategy is simplified. But this method needs to change sub-modules' structure, which increases the cost of hardware and the volume of the system. Besides it has a strong dependence on the DC bus. The literature [12-13] presents a two stage charging method which can charge multiple sub-modules at the same time. By using double closed-loop control strategy, it can charge sub-modules which have been charged by uncontrolled charging method to set-point. This method can avoid overcurrent in charging process, and has a better DC voltage characteristic. Because of the double loop control strategy, it is difficult to adjust PI parameters. So the system characteristics are often based on the experience of the designers.

Sub-module capacitor voltages reaching the initial value is a prerequisite for the normal operation of the system. Based on the analysis of the uncontrolled charging method, this paper proposes a simple self-excited selection pre-charge control strategy.

2. Topology and Operation Principle

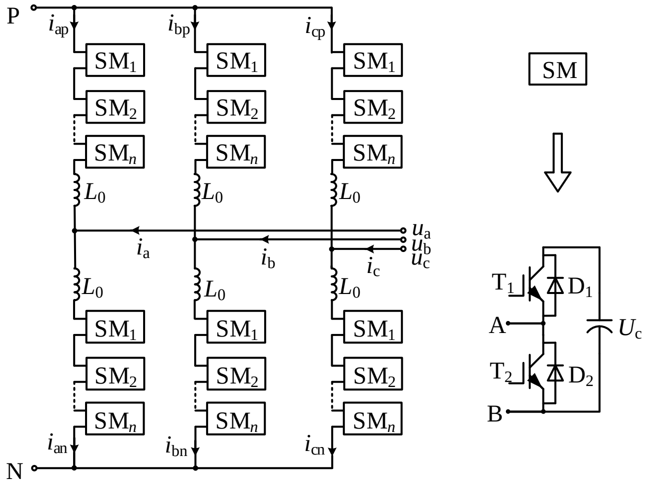

Figure 1. Topology of MMC and Schematic Diagram of SM

Figure 1 illustrates the structure of double star chopper cells. Each phase consists two similar arms which comprise *n* sub-modules and a reactor. Upper and lower arms of three phase are connected with common DC bus P and N. AC voltage comes from electrical connections of upper and lower arm reactors. As illustrated in figure 1, i_{ap}, i_{bp}, i_{cp} are upper arm current of phase *a*, phase *b* and phase *c*, respectively. i_{an}, i_{bn}, i_{cn} are lower arm current of phase *a*, phase *b* and phase *c*, respectively. i_a, i_b, i_c are arm current of phase *a*, phase *b* and phase *c*, respectively. u_a, u_b, u_c are arm voltage of phase *a*, phase *b* and phase *c* respectively.

The sub-modules are important parts of arm, implemented by three ways, full bridge sub-module, half bridge sub-module and clamp double sub-module [14-15]. Full bridge and clamp double sub-module can remove fault current by controlling switch state when system has trouble with DC side, but it needs more switching devices. This paper analyzes precharge process of half-bridge sub-module which has more application. Half-bridge sub-module consists two IGBTs with an anti-parallel diode and a polar capacitor. By controlling the stage of IGBTs, we can control output voltage of sub-module.

According to the states of IGBTs and the directions of current, sub-module has three kinds of operation modes. When all IGBTs work, sub-module capacitor will be shorted. And we should avoid this situation when system is in operation.

Table 1 and Figure 2 illustrate the operation modes and current path.

Table 1. Operation Modes of Sub-module

The direction of current	T_1	T_2	D_1	D_2	The stage of capacitor
A→B	0	0	1	0	Charge
B→A	0	0	0	1	Bypass
A→B	0	1	0	0	Bypass
B→A	0	1	0	1	Bypass
A→B	1	0	1	0	Charge
B→A	1	0	0	0	Discharge

Mode 1. When all IGBTs are turned off, current flows through the diode D_1 and the capacitor or the diode D_2, so the capacitor will be charged or bypassed. Without driving IGBT, this mode can charge capacitor voltage to a certain value. This mode is called uncontrolled charging method

Mode 2. When IGBT T_1 is turned off and T_2 is turned on, current flows through the IGBT T_2 or capacitor and diode D_2, so the capacitor will be bypassed. Capacitor voltage is stable when IGBTs work on this mode.

Mode 3. When IGBT T_1 is turned on and T_2 is turned off, current flows through the diode D_2 or IGBT T_1, so the capacitor will be charged or discharged.

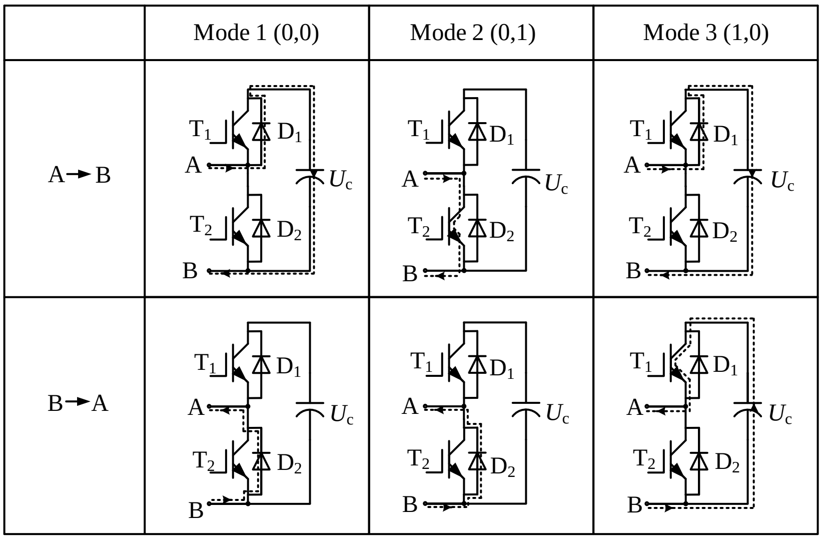

Figure 2. Current Paths of Sub-module

3. Uncontrolled Charging Method

During uncontrolled charging method stage, all IGBTs are turned off. Current flows through the diodes and the capacitors. Without driving IGBTs, it is widely used in the system that IGBT drive voltage is generated by capacitor voltage.

In a charging period, the expressions of capacitor voltage can be described by formula (1).

$$\begin{cases} U_c(t_n)=U_c(t_{n-1}), & \text{when } i\le 0 \\ U_c(t_n)=U_c(t_{n-1})+\dfrac{1}{C}\int_{n-1}^{n} i(t)\,\mathrm{d}t, & \text{when } i>0 \end{cases} \tag{1}$$

where i is the arm current, with its positive direction shown in Figure 1.

In the early stage of uncontrolled charging method, capacitor voltages are low. And the path of current only is concerned with the instantaneous value of line voltage. Take phase a and phase b as examples. When $u_{ab}>0$, the capacitors of the upper arm of phase b and the lower arm of phase a will be charged, and the capacitors of the lower arm of phase b and the upper arm of phase a will be bypassed. Otherwise, the capacitors of the upper arm of phase *a* and the lower arm of phase *b* will be charged, and the capacitors of the lower arm of phase *a* and the upper arm of phase *b* will be bypassed. The charging process of other phases are similar to this situation that the capacitors of the upper arm whose phase voltage is highest are bypassed, and the capacitors of the lower arm whose phase voltage is highest are charged. As for the other phase, the capacitors of the upper arm are charged, the capacitors of the lower arm are bypassed.

Figure 3 illustrates the equivalent circuit diagram of this situation. As the sub-module capacitor voltage increases, only two arms are charged. We assume instantaneous values $ua>ub>uc$， $u_{ac}>\sum U_c>u_{ab}$ for convenient analysis, and equivalent circuit is shown in figure 8 dotted line. At this time, the capacitors of the lower arm of phase *a* and phase *c* are charged. There exists no current in phase *b* whose diodes are turned off. Other equivalent circuit diagrams are similar.

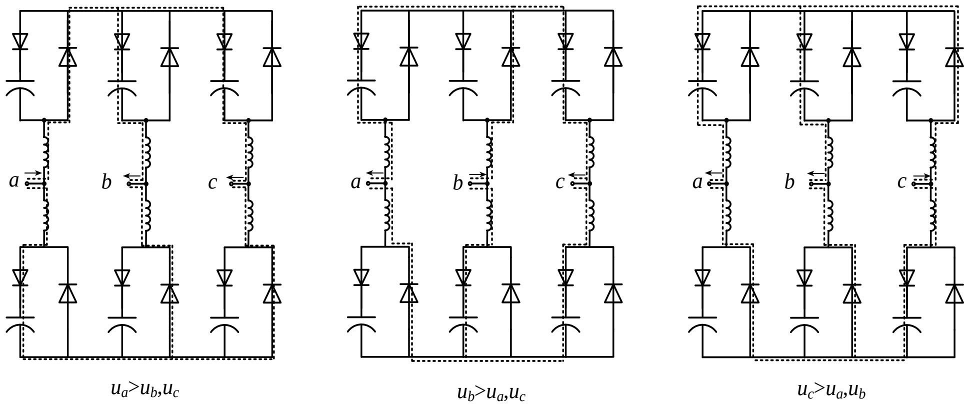

Figure 3. Early Stage Equivalent Circuit of Uncontrolled Charging Method

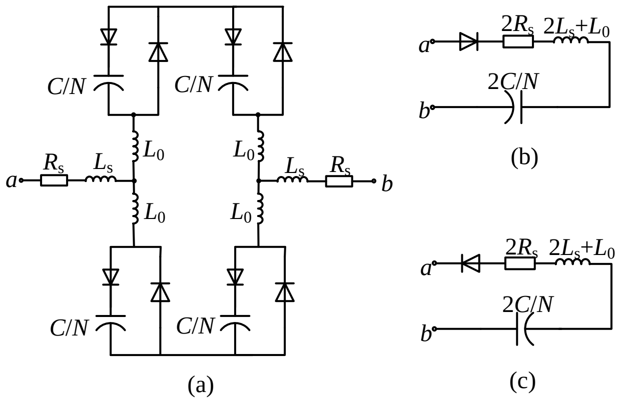

Figure 4. Charging Circuit of Phase-*a*-to-Phase-*b*.
(a) Equivalent Circuit. (b) Simplified Circuit when i_{ab}>0. (c) Simplified Circuit when i_{ab} <0.

Due to rotational symmetry of MMC, this paper gives an example of the equivalent charging loop between phase-*a* and phase-*b*, and it is shown in Figure 4. *C*, L_0, R_s, L_s are the equivalent capacitance, equivalent inductance of the arm, equivalent resistance and equivalent inductance of the source grid, respectively.

By Kirchhoff’s voltage law, the characteristics can be described by

$$\begin{aligned} \dot{U}_{ab} &= 2\dot{I}_{ab}R_s + j\dot{I}_{ab}X \\ X &= \omega\left(2L_s + L_0\right) - \frac{N}{2\omega C} \end{aligned} \tag{2}$$

Thus,

$$I_{ab(max)} = \frac{U_{ab}}{\sqrt{4R_s^2 + X^2}} \tag{3}$$

where $U_{ab} = \sqrt{3}U_m$, U_m is the peak of the phase voltage.

Thus, the current limiting resistance can be described by

$$R_s = \frac{1}{2}\sqrt{\left(\frac{U_{ab}}{I_{ab(max)}}\right)^2 - X^2} \tag{4}$$

From simplified circuit, we can know the time constant

$$\tau = 2R_s \bullet \frac{2C}{N}. \tag{5}$$

Because of the length of the time that an arm is charged takes 1/3 of total length of time, the time constant should be adjusted to

$$\tau = 2R_s\frac{2C}{N} \times \frac{3}{1} = 12\frac{R_sC}{N}. \tag{6}$$

As Figure 4 shows, the maximum value of capacitor voltage can be described by

$$U_{c(max)} = \frac{\sqrt{3}U_m}{N} \tag{7}$$

Hence, sub-module capacitor voltage can be described by

$$\begin{aligned} U_c &= \frac{\sqrt{3}U_m}{N}\left(1 - e^{-\frac{t}{\tau}}\right) \\ \tau &= 12\frac{R_sC}{N} \end{aligned} \tag{8}$$

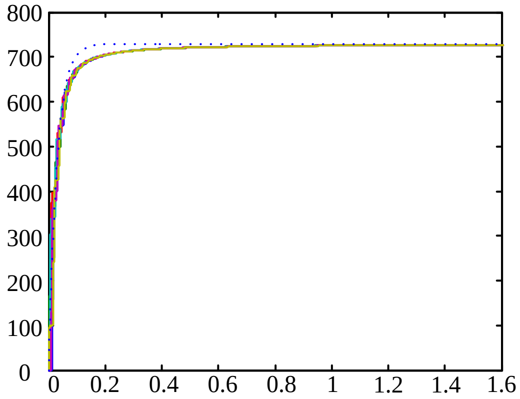

Figure 5. Capacitor Voltage Waveform of Uncontrolled Charging Method

Figure 5 illustrates capacitor voltage simulation and deduction waveform of uncontrolled charging method (detailed parameters are shown in Table 2). Solid lines in the figure are all sub-modules capacitor voltage simulation waveform, while dashed line is deduction waveform. Simulation waveform is basically in coincidence with deduction waveform. Theoretical expressions being assumed continues charging current and reactors without voltage drop, leading to the deviation. As formula (7) illustrates the maximum value of the sub-module capacitor voltage is 1/N of line voltage after uncontrolled charging method completes. Thus, further charging is necessary.

4. Selection Charging Method

Seen from the charging process and formula (7) illustrate, the reason why sub-module capacitor voltage can't reach the given value is that multiple sub-modules are charged. So we should reduce the number of sub-modules charged at the same time, which can charge capacitor voltage to the desired value. To overcome the deficiencies of uncontrolled charging method, this paper presents a selection charging method. It can not only reduces the number of sub-modules which are charged at the same time, but also drives the third phase which is bypassed to open.

The procedure of selection charging method is designed in Figure 6.

1. Sort capacitor voltages and determine the *m* lowest voltage sub-modules.

2. Turn on IGBT T_1 and turn off IGBT T_2 of these *m* sub-modules (call this condition turn on sub-module), and turn off IGBT T_1 and turn on IGBT T_2 of other sub-modules (call this condition turn off sub-module).

3. Turned off all arm sub-modules, when arm current is less than zero.

Figure 6 and Figure 7 illustrate arm flow chart and equivalent circuit.

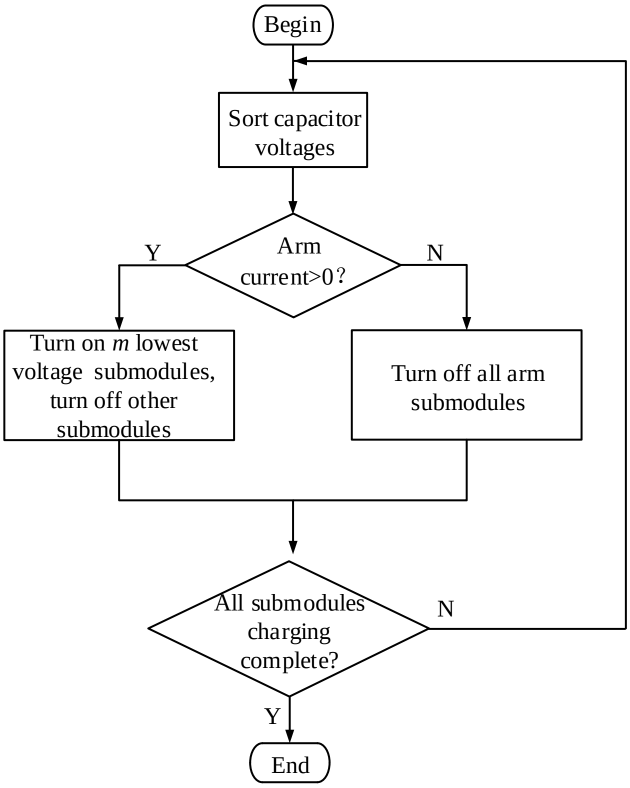

Figure 6. Flow Chart of Selection Charging Method

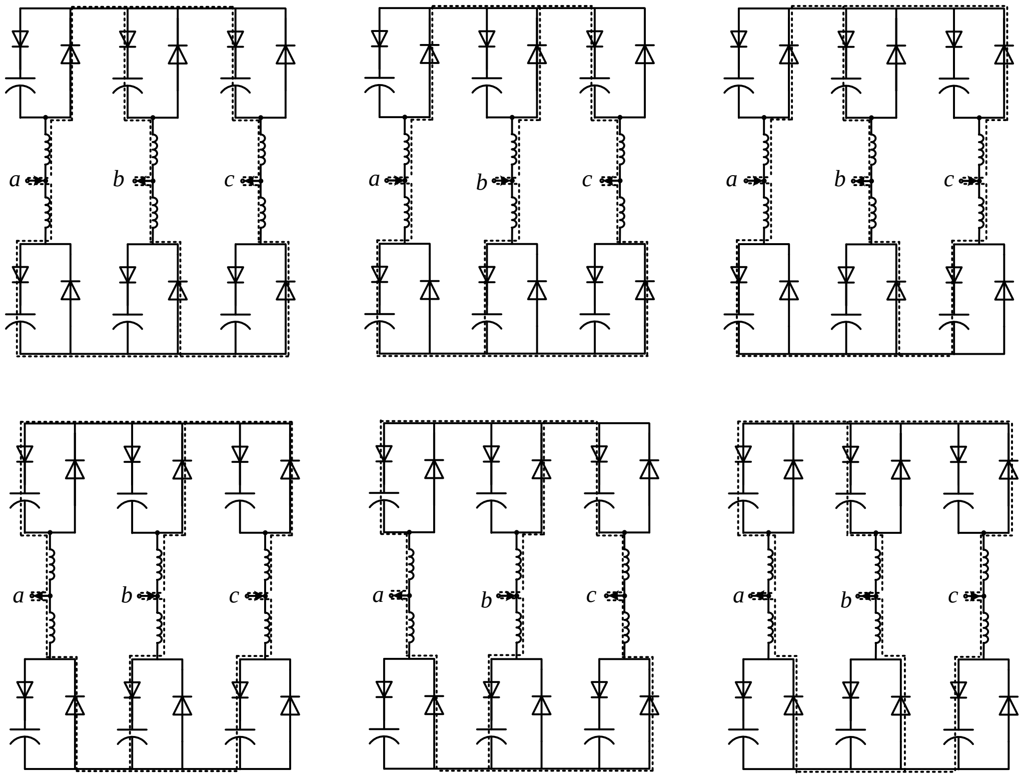

Figure 7. Equivalent Circuit of Pre-charge

As the equivalent circuit diagram shows, selection charging method can charge three arms at the same time. Figure 8 illustrates the equivalent circuit of the last period of uncontrolled charging method and the particular time of selection charging method. Solid line in the figure is the equivalent circuit of selection charging method. Dashed line is the equivalent circuit of late uncontrolled charging method. By uncontrolled charging method only two arms can be charged at the same time. The maximum of OP voltage is the peak of the line voltage, and no current flows through phase *b*. By selection charging method three arms can be charged at same time, and upper arm reactor of phase *b* is discharged, and the maximum OP voltage is larger than line voltage. So sub-module capacitor voltage is larger than $\sqrt{3}U_m/m$.

In order to prevent sub-module capacitor voltage for being overcharged, controller should bypass all sub module or put system into normal operation as soon as possible.

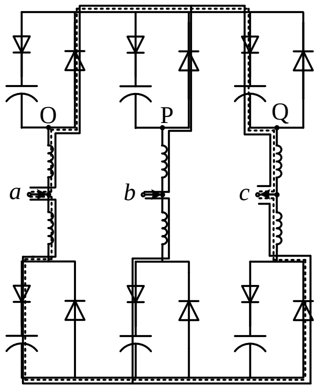

Figure 8. Circuit of Uncontrolled Charging Method and Selection Charging Method

5. Simulation and Experiment Results

In order to verify the correctness of the analysis and pre-charge strategy, simulations are carried out in Matlab/Simulink. Main parameters are listed in Table 2.

Table 2. Main Parameters of Systems

Parameter	Digital simulation	Physical experiment
AC system Line-Line voltage	35kV	25V
Arm reactor	53mH	5mH
AC reactor	5mH	4mH
Current limiting resistance	20Ω	10Ω
DC capacitance	6mF	1.88mF
Cascade number per arm	48	4
Capacitor voltage reference	1250V	25V
Charged number *m*	1	1

Figure 9 illustrates all sub-modules capacitor voltages waveform of simulation. When time reaches 0.15s, capacitor voltages will reach the maximum value by uncontrolled charging method. By this method, voltages rise very slowly. At this time, the modulation strategy will change from uncontrolled charging method to selection charging method in order to charge more. At the time of 1.3s capacitor voltages reach the desired value 1250V.

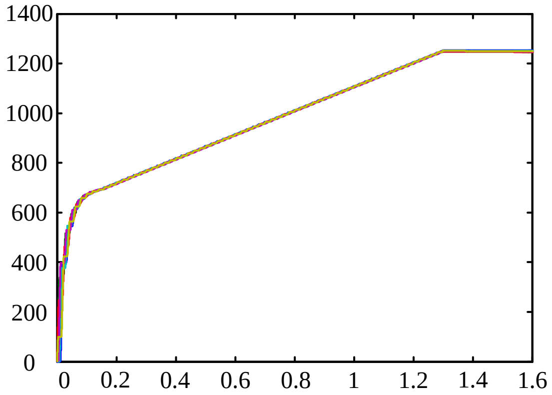

Figure 9. Simulation Waveform of Sub-modules Capacitor Voltage

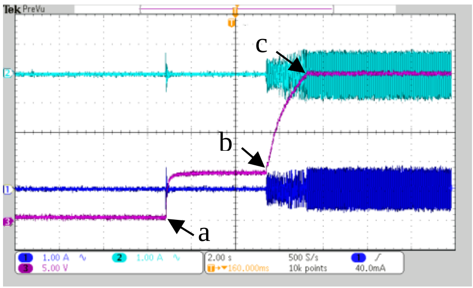

Figure 10. Experiment Waveform of Sub-module Capacitor Voltage and Arm Current (Phase *a*, Upper Arm)

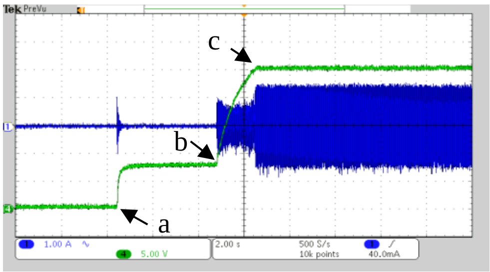

Figure 11. Experiment Waveform of Sub-module Capacitor Voltage and Phase Current (Phase *a*, Upper Arm)

Capacitor voltage and arm current (phase a, upper arm) are given in Figure 10. Channel 1 is upper arm current waveform of phase *a*, and channel 2 is lower arm current waveform of phase *a*, while channel 3 is upper arm first sub-module capacitor voltage waveform of phase *a*. At the time of a point, the system will be in the stage of uncontrolled charging. And capacitor voltages increase to maximum value $25\sqrt{2}/4$=8.84V. The experimental results are consistent with theoretical derivation. At the time of b point, the system will be in the stage of selection charging. And capacitor voltages continue to increase to the desired value 25V.

Sub-module capacitor voltage and phase current (phase a, upper arm) are given in Figure 11. Channel 1 shows phase *a* current waveform, and channel 4 is the first sub-module capacitor voltage waveform of upper arm in phase *a*. At the uncontrolled charging method stage, maximum phase current of phase *a* is $25/(2\times10)=1.25$A. The experimental results are consistent with theoretical derivation. At the time of c point, all sub-modules are bypassed, and circuit resistances are reduced. Control strategy of rectifier should be put in reality, and circuit current will depend on control strategy and load.

5. Conclusions

The pre-charge of the capacitors in sub-modules is essential to the normal operation of the modular multilevel converter. This paper analyzed the process of uncontrolled charging method and equivalent circuit, based on which, calculation formula of sub-module capacitor voltages was derived.

Uncontrolled charging method is widely used in the system that IGBT drive voltage is generated by capacitor voltage.

The method of selection pre-charge method of MMC proposed in this paper could rise the capacitance voltage to the desired value. There is no need to add auxiliary equipment and simple control strategy which are major advantages of this method. Besides, it can be used in rectifier or inverter system.

In order to avoid the overcharge of capacitance voltage, the system should be immediately changed to rectifier system.

Acknowledgments

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