An Improved Drive Signal Exchange Strategy for Cascaded H-Bridge Topology

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***Abstract*—In order to solve the inherent problem of 'even power distribution' or 'dc-link capacitor voltage balance' in the cascaded H-Bridge topology, the so called drive signal exchange scheme is always employed. However, the conventional exchange scheme ignores the problem of extra switching during the execution process which increases switching losses. The cause of switching cost increase during exchange process is deeply analyzed in this paper. In order to solve this problem, taking all kinds of potential exchange cases into consideration, this paper proposes an improved strategy which can eliminate extra switching totally. This algorithm makes a full use of the natural PWM action and optimize the exchange procedure to realize the switching states exchange. Finally, the validity and effectiveness of the proposed strategy is confirmed by several experimental tests on a seven-level cascaded H-bridge system.**

Keywords—Multilevel converter, cascaded H-bridge, signal exchange strategy, switching losses decrease.

I. INTRODUCTION

Multilevel converters have attracted significant interests from researchers due to their outstanding features for high power/voltage applications. Compared with two-level converter, the salient features of multilevel converters mainly include: (1) using devices rated at lower voltage for high-power applications; (2) smaller filter requirement; (3) lower distorted waveform; (4) lower common-mode voltages and reduced electromagnetic interference (EMI); (5) fault-tolerant operation [1]- [3].

Currently, the cascaded H-Bridge (CHB) is one of the most popular multilevel topologies applied in industrial applications [4]- [5]. It is capable of achieving medium output voltage level using only low-voltage mature switching devices. Modularity and scalability are another two important merits of CHB, making the hardware implementation and maintenance rather simpler than other multilevel converters. Based on these worthy features, the CHB topology can be utilized as inverters in traction applications [6] and solar systems [7], pulse-width modulation (PWM) rectifiers [8], static synchronous compensator (STATCOM) [9], solid-state transformer (SST) [10] and so on.

Due to the modular structure of CHB topology, the PWM signals for different H-bridge (HB) cells can be swapped with each other without impact on system output. Based on this property, the exchange of PWM drive signals among different HB cells is popular in CHB for some particular purposes [11]- [17]. For example, the switching pattern for devices in HB cells should rotate in order to evenly distribute the switching and conduction losses under phase-disposition PWM [11]. The uneven power distribution among HB cells caused by hybrid modulation technique can also be effectively compensated by switching rotation scheme [12] [13]. When the CHB serves as a rectifier, drive signals sorting strategy is an important method for regulating DC-link capacitor voltages [14]- [17]. Previous studies about drive signal rotation or exchange mainly focus on the aspects of stable operating region, voltage dynamic response, modularity and losses distribution. However, another problem that the number of power device actions increase during exchange process has been neglected by most of researchers. This is a serious problem on account of the drive signal swapping among HB parts being frequent in many applications [13]- [17]. Therefore, if the swapping procedure is done without careful design, there will be a sharply increase of total switching losses in the CHB system compared with no signal exchange happening.

In order to solve the problem mentioned above, a detail analysis about the phenomenon of switching losses increase caused by drive signal exchange process is made in this paper. And then, a novel drive signal exchange strategy is presented which can reduce the switching losses generated by signal exchange. Based on this strategy, the extra device actions can be totally eliminated during exchange procedure. In practical applications, the proposed strategy which can be easily implemented with a simple DSP processor, is valid for any number of HB cells. At the end of this paper, the feasibility and effect of this signal exchange strategy is verified by experimental results.

II. CHB TOPOLOGY AND MODULATION

The structure of CHB topology is shown in Fig.1. As for modulation, the most common method is that only one HB cell works in 'PWM' mode while others maintain constant output. If the nominal value of HB capacitor voltage is E, the working states of cells and their corresponding switching sequences are summarized in Table I, where 1 means that the device is gated and 0 means off. As shown in Table I, the 'PWM' mode can be further divided to 'PWM1' mode (HB output between 0 and E) and 'PWM2' mode (HB output between 0 and -E). If there is no working mode exchange among HB cells, the total action times of power devices during one carrier period for n-cell

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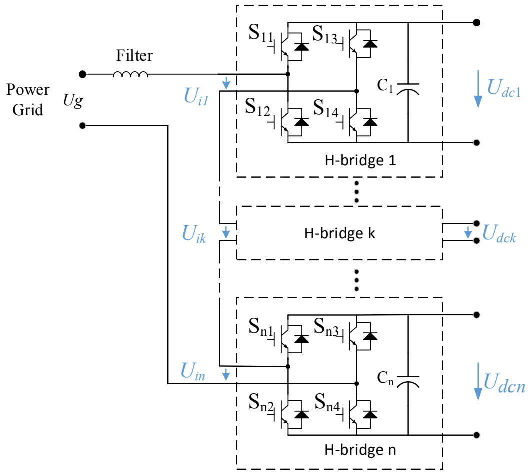


Fig. 1. A CHB system composed of n HB cells

Table I: The working modes of HB cell and corresponding switching states

Working Mode	Switching States (S_{k1} - S_{k4})	H-bridge Output (U_{ik})
'+E'	'1 0 0 1'	+E
'PWM1'	'1 0 0 1'	+E
	'0 1 0 1'or '1 0 1 0'	0
'0'	'0 1 0 1'or '1 0 1 0'	0
'PWM2'	'0 1 0 1'or '1 0 1 0'	0
	'0 1 1 0'	-E
'-E'	'0 1 1 0'	-E

CHB system are four apparently as only one cell works in the 'PWM' mode.

III. The Extra Switch During Conventional Exchange Process

Due to modular structure in CHB topology, the function and effect of each HB cell are all the same. Therefore, the drive signals of every HB module can be swapped with each other with no impact on the output. This method is widely applied in practical applications for the reason such as capacitor voltage regulation and equalizing losses distribution. At present, the generation of drive signals and implementation of signal exchange algorithm for CHB are mostly realized by digital controller such as DSP or FPGA. In the digital control, drive signals are switched either at the bottom or the top of carrier wave in the interrupt program generally. When the exchange time or participants are inappropriate, the action frequency of power switching devices increase compared with no any changes. It causes switching losses rising up for the whole system. There are two kinds of circumstances resulting in the phenomenon of switching losses increase.

A. Switching between '±E' mode and '0' mode

Based on Table I, switching states of HB cell operating in the '+E' mode or '–E' mode are certain. As for '0' mode, there are two conduction paths for this output, the corresponding switching sequences of which are '0101' and '1010', respectively. It can be found that there are two switching states different between '±E' mode and '0' mode no matter what conduction paths chosen for '0' mode. Therefore, when the drive signals swaps between '±E' mode and '0' mode, there will be four extra action times of power devices. EXAMPLE1 is given to further explain this phenomenon. In this example, there are three HB cells in the CHB system named a, b and c. Before the exchange happening, the cell a works in the 'PWM1' mode with cell b in 'E' mode and cell c in '0' mode. S_{a1} and S_{a2} are driven by high frequency PWM signal determined by the size comparison between modulation wave and carrier wave, while the states of S_{a3} and S_{a4} are 0 and 1, respectively. Therefore, the state of S_{k3} (k= a, b and c) is always equal to 0 and the state of S_{k4} is also constant as 1 in the three cells. They don't change their states no matter whether the drive signal exchange happens. Hence, the analysis about S_{k3} and S_{k4} can be omitted. In addition, the analysis for S_{k1} is enough for drive signals of S_{k1} and S_{k2} are complementary. The drive signals of S_{k1} in EXAMPLE1 are shown in Fig.2 with no signal exchange happening and only S_{a1} changes its states two times in every carrier period. If there is a drive signal exchange happening on the top of the carrier wave labeled in Fig.3, the drive signals of cell b and cell c are swapped. The switching state of S_{b1} jumps to one while S_{c1} drops down at the moment. These states variations are caused by signal commutation between cell b and cell c, making power device action frequency increase in contrast with no changes presented in Fig.2. Taking the complementary devices S_{b2} and S_{c2} into consideration, this exchange process will bring 4 extra action times in total which is also the source of switching losses increase mentioned above.

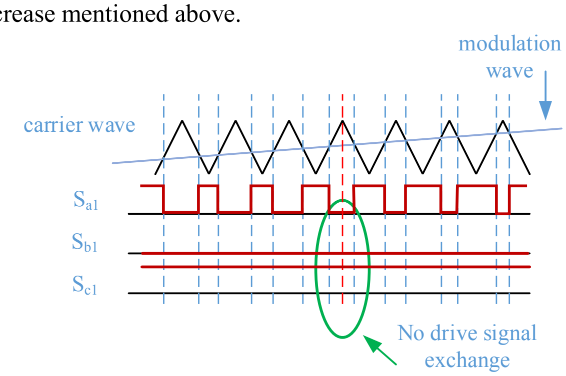


Fig. 2. Schematic diagram of EXAMPLE1 with no drive signal exchange.

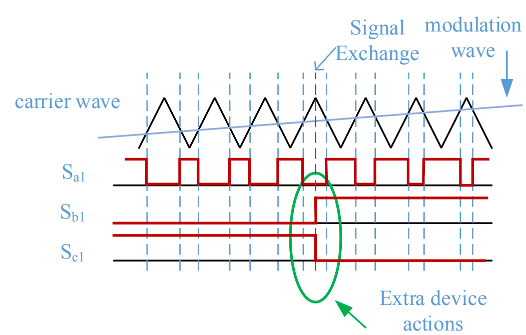


Fig. 3. Schematic diagram of EXAMPLE1 with drive signal exchange between cell b and cell c.

As for exchange process between '-E' and '0' or signal exchange occurrence at the bottom point of the carrier wave, the phenomenon of action frequency increase taking place in EXAMPLE1 can also appear. The four extra action times is inevitable in this circumstance if no additional optimization method is added.

B. Switching between 'PWM' mode and another mode

In this circumstance, whether the action times increase depends on exchange time and participators. Since there are various cases in this circumstance, only one typical instance is given through EXAMPLE2 to illustrate this problem and the same analysis process is also suitable for other cases. The EXAMPLE2 is also based on a three cells CHB system whose original working modes are identical with EXAMPLE1. Suppose that the exchange is triggered at the bottom of the carrier wave and drive signals of cell a and cell b are swapped. As defined in Chap.2, switching states of S_{a1} to S_{a4} are certain at '1001' at bottom of the carrier wave based on 'PWM1' mode. Therefore, there are four extra device action times in total appearing during the exchange process between cell a and b, which means switching frequency is double. The signal exchange schematic diagram of EXAMPLE2 is presented in Fig.4. However, if the exchange occurs between cell a and cell c at the bottom of the triangular wave, there will be no changes in the number of device action times. The reason is that the switching states for cell c are '1001' which is totally identical with 'PWM1' mode at the bottom of the carrier wave. The exchange process doesn't change any transient states for the whole system at the exchange moment. Analogously, the mode-exchange between cell a and cell c at the top of the triangular wave will also increase the action times of power devices while exchange between cell a and cell b will not at this moment. The analysis about 'PWM2' mode is similar, thus not repeated here.

According to explanation mentioned above, as long as switching states between the 'PWM' mode and another target mode are different at the exchange moment, there must be four extra device action times generation. Otherwise, the exchange process has no effect on the number of device actions.

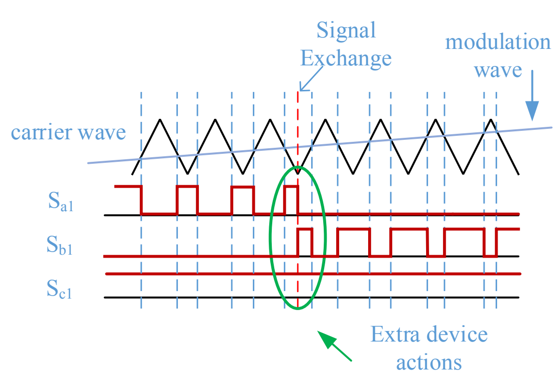


Fig. 4. Schematic diagram of EXAMPLE2 with drive signal exchange between cell a and cell b.

IV. Proposed Drive Signal Exchange Strategy

A proposed drive signal exchange strategy is put forward in this section which can avoid switching losses increase totally during the exchange process. In the conventional exchange scheme, there are not any additional limitations for the exchange moment and modes. However, in this proposed strategy, the exchange process is carefully designed to eliminate extra action times based on the two principles as follows:

- If modes involved in the exchange process don't include 'PWM' mode, (Circumstance A in the Chap.3), it must switch to 'PWM' mode as transition at first and then realize the final mode.
- When the exchange process happens between 'PWM' mode and other mode (Circumstance B in the Chap.3), the exchange time is prescriptive depended on the condition of carrier wave. If the exchange time is at the bottom of carrier wave, only the exchanges between 'PWM1' mode and '+E' mode or 'PWM2' mode and '0' mode are permitted. Other exchange should proceed at the top of the carrier wave.

In the digital control system, the exchange is usually carried out at the top or bottom of the carrier wave. The proposed strategy follows this custom. The block diagram of this proposed exchange strategy is shown in Fig.5 and Fig.6. It fully considers various circumstances and the phenomenon of device action times increase during exchange process can be totally eliminated based on this strategy. In implementation process, it should judge whether the exchange includes 'PWM' mode firstly. If one of the exchange participant is 'PWM' mode, only cells whose switching states are identical with 'PWM' mode can be swapped with it at the execution moment. For instance, at the bottom of the carrier wave, the switching states of 'PWM1' mode are the same as '+E' mode while the switching states of 'PWM2' mode are uniform with '0' mode. Therefore, only the two kinds of swaps can be done at the bottom of the carrier wave and other swaps must be executed at the top of the carrier wave. If the swap doesn't meet the condition, participant cells should reserve last modes at the exchange moment and postpone the execution half of the carrier cycle.

If the participants of exchange don' t include 'PWM' mode, this circumstance is more complex. According to the analysis before, it's impossible to achieve the exchange between '±E' mode and '0' mode without increasing device action times in the conventional scheme. So a novel three-step exchange strategy is put forward which utilizes 'PWM' mode as a transition state to solve this problem. The detailed procedure for this type of exchange is shown in Fig.6.

In order to illustrate the proposed exchange strategy more expressly, the two examples shown in Chap.3 are analyzed again. In EXAMPLE1, the initial switching states of S_{a1}, S_{b1} and S_{c1} are shown in Fig.2 while target states are presented in Fig.3. To avoid switching losses increase caused by signal exchange, two transition stages should be inserted to this process. The three steps of this signal exchange are listed as follows:

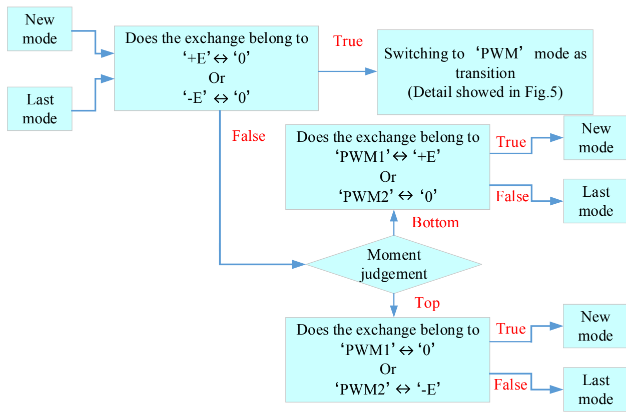


Fig. 5. Block diagram of the proposed drive signal exchange strategy.

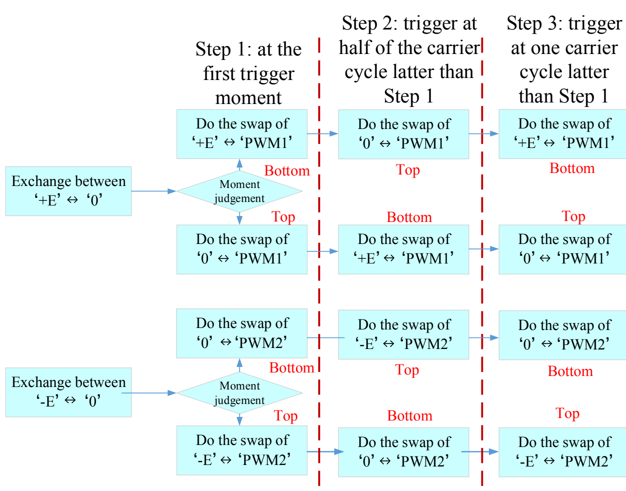


Fig. 6. Block diagram of strategy when the participants of exchange excluding 'PWM' mode.

STEP 1: Swap the drive signals between cell a and cell b. It's clear that the switching states of cell a ('PWM1' mode) and cell b ('0' mode) are both '0101' at the top of the carrier wave. Therefore, signals swap between them won't cause extra action times. After this step, the cell a is under '0' mode and cell b works at 'PWM1' mode. The cell c still operates at '+E' mode.

STEP 2: Swap the drive signals between cell b and cell c. The step 2 is triggered at the bottom of the carrier wave which is half of the carrier cycle latter than step 1. The cell b works at the 'PWM1' mode and switching states are '1001' at this exchange moment, which are the same as cell c. Hence, this swap does not cause switching frequency increase as well. After step 2, the modes of cell a, b and c are '0', '+E' and 'PWM1', respectively.

STEP 3: Swap the drive signals between cell a and cell c. The step 3 is triggered at the top of the triangular wave which is one carrier cycle lag of step 1. Analogously, the signals swap between cell a ('0' mode) and cell c ('PWM1' mode) doesn't add device action times in the system due to identical switching states between the two cells. After step 3, the final mode of each cell is achieved which are 'PWM1', '+E' and '0', respectively.

Via these three steps, the final states are identical to the old method but there are no switching losses increase during this process. The switching states of S_{k1} in this swap procedure are shown in Fig.7 based on the proposed strategy and analysis given above. Compared with Fig.3, the extra device actions caused by signal exchange are eliminated and total device action times are the same as the case without signal exchange, which is exhibited in Fig.2.

In EXAMPLE2, the initial switching states are identical with the first example shown in Fig.2 and the target states are presented in Fig.4. The phenomenon of action times increase in this example is caused by improper exchange moment. Based on the proposed strategy mentioned above, the exchange should delay half of the carrier cycle to take place. After half of the carrier period, the exchange moment changes to the top of the triangular wave. At this time, the exchange states of cell a are certain at '0101' which are the same as the swap target cell b. Therefore, the extra device actions caused by exchange process are removed at this switchover moment. The detailed exchange procedure under the proposed strategy is shown in Fig.8. Comparing with the unimproved case, it can be found that switching frequency under this strategy is less than the case shown in Fig.4 and identical with no exchange taking place. The switching losses increase is avoided under this strategy.

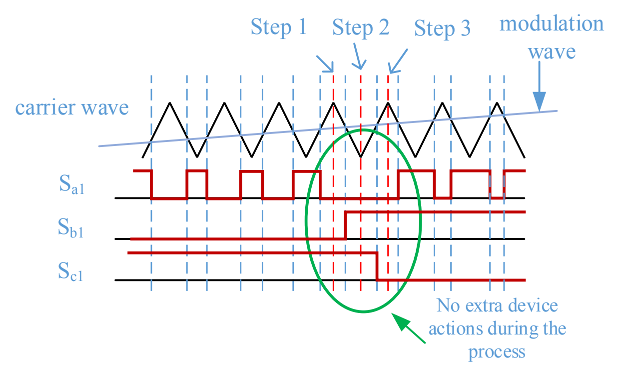


Fig. 7. The swap procedure of EXAMPLE1 under the proposed strategy

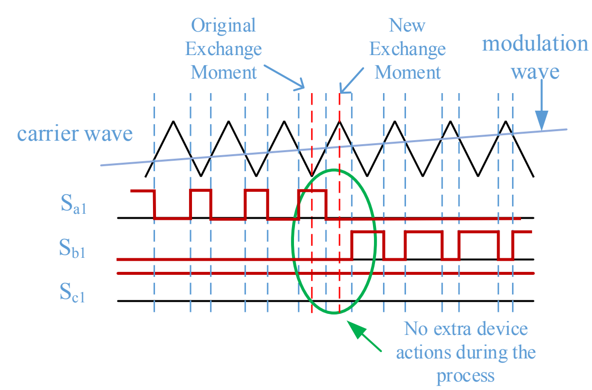


Fig. 8. The swap procedure of the EXAMPLE2 under the proposed strategy

V. EXPERIMENTAL RESULTS

A seven-level CHB system has been constructed in order to verify the validity of the proposed signal exchange strategy. Three HB cells are contained in this CHB system and the nominal value of HB dc side voltage is 100V. The control system of the experimental prototype is implemented using a TMS320F28377 digital processor. The first experiment result shown in Fig.9 is the output voltage of the CHB system. The output result is identical regardless of whether the proposed exchange strategy is enabled. It also proves the application of the proposed strategy has no impact on the output of system. The reason is that this strategy only reallocates drive signals among HB cells during the exchange process and makes no difference to the synthetic output wave.

In Fig.10, the circumstance of EXAMPLE1 analyzed in Chap.3 and Chap.4 is carried out in this experimental prototype. The carrier wave frequency is 10kHz and the output voltage of the CHB is in the range of 100V to 200V when the signal exchange happens. Initially, the cell a works in 'PWM1' mode; cell b is in the '0' mode and cell c is in the '+E' mode. At the exchange moment, the drive signals of cell b and cell c are swapped on the top of the carrier wave. In order to facilitate the analysis, only the drive signals of first the power device in three cells, S_{a1}, S_{b1} and S_{c1}, are presented. In Fig.10 (a), it can be found two more device action times are generated on S_{b1} and S_{c1} during the exchange process. Taking their complementary power devices into consideration, there are four more device action times caused by this swap for the whole CHB system. Adopting the suggested exchange strategy, the process are translated to Fig.10 (b). It shows that drive signals exchange between cell b and cell c is achieved perfectly, without introducing extra device action times.

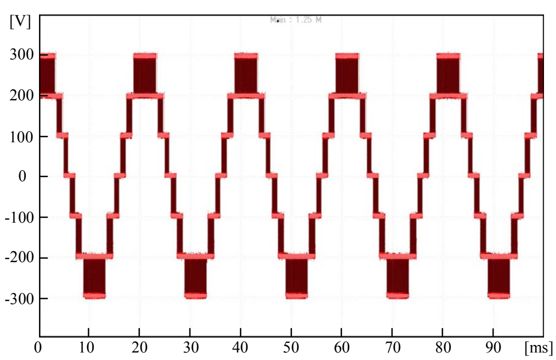


Fig. 9. The seven-level output voltage of the CHB system.

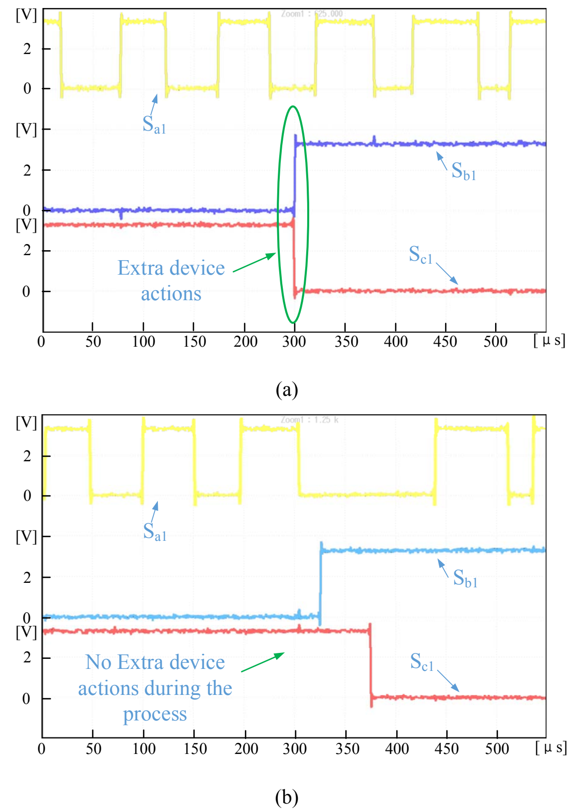
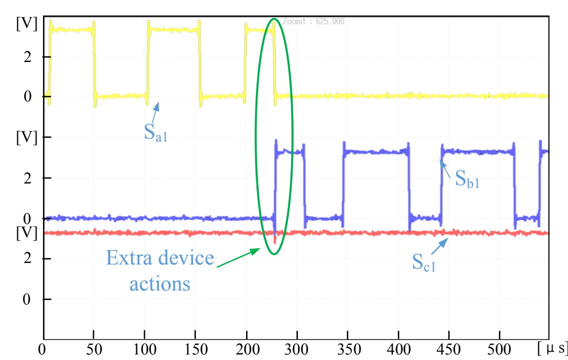
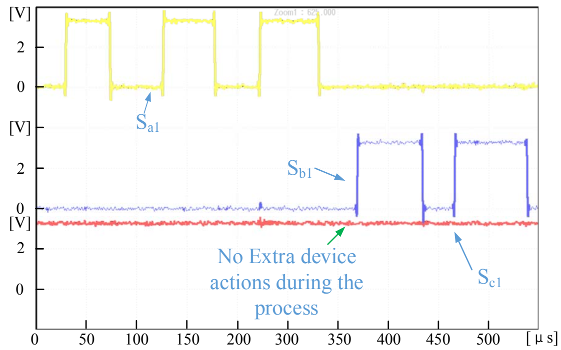


Fig. 10. The drive signal exchange process of cell b and cell c. (a) drive signal exchange with no treatment. (b) drive signal exchange under the proposed strategy.

The experimental results of EXAMPLE2 researched in Chap.3 and Chap.4 are exhibited in Fig.11. The three cells' working modes before exchange occurrence are identical with the EXAMPLE1. When the exchange takes place, there is a signal swap between cell a and cell b at the bottom of the triangular wave. Comparing Fig.11 (a) with Fig.11 (b), it is easy to discover that extra device actions during the exchange



(a)



(b)

Fig. 11. The drive signal exchange process of cell a and cell b. (a) drive signal exchange with no treatment. (b) drive signal exchange under the proposed strategy.

process are avoided after adopting this strategy. Thereby, total switching losses are reduced in contrast with no treatments.

To sum up, experimental results shown in Fig.10 and Fig.11 are exactly consistent with the analysis conducting in Chap.3 and Chap.4. These results demonstrate that the power device action frequency is constant no matter whether the exchange happens utilizing this strategy. The phenomenon of switching losses increase during the exchange process can be totally eliminated by the proposed method.

VI. Conclusion

In this paper, a novel drive signal exchange strategy is presented for CHB system to avoid the defect of device action times increase during the exchange process. The suggested strategy is easy to implement and won't produce other costs for the system. It can serve as an independent software module added into CHB system without impact on other parts. The effect of this strategy is obvious and it can fully eliminate the phenomenon of switching frequency increase during the exchange process. The accuracy of the theoretical analysis has been verified by experiment and results show that the strategy works very well in various circumstances. Besides, the application of this proposed strategy is not limited to CHB system. Other modular structure topologies, such as modular multilevel converter, can also utilize this strategy when they adopt signal exchange method in the modulation.

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