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ScienceDirect
Procedia Earth and Planetary Science 1 (2009) 1554–1560
Procedia Earth and Planetary Science
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The 6th International Conference on Mining Science & Technology

Flying capacitor multilevel inverters with novel PWM method

Miao Chang-xin[a,]*, Shi Li-ping[a], Wang Tai-xu[a], Cui Cheng-bao[b]

[a] *College of Information and Electrical Engineering CUMT,Xuzhou 221008,China*
[b] *Zaozhuang Mining (Group) Co., Ltd. Zaozhuang 277000, China*

Abstract

Flying capacitor multilevel inverters are increasingly used in industry applications. In order to improve the harmonic performance of the output voltage under low modulation index region, the paper presents a novel PWM method for flying capacitor multilevel inverters based on the idea of controlling freedom degree. The novel PWM method can balance the flying capacitor voltage in a certain period. The validity of the novel PWM method is demonstratedby the experimental results.

Keywords: flying capacitor; multilevel inverters; control freedom degree; PWM

1. Introduction

Recently, with the rapid development in electrotechnics fields, the equipment of power electronics is expected to handle the higher ratings of voltage and capacity, so multilevel inverters have drawn the tremendous interests under this background. Flying capacitor multilevel inverters are increasingly used in industrial applications because it is easier to be extended to multilevel inverter than diode clamped inverter [1][2][3]. For flying capacitor multilevel inverters, the most common PWM method is the phase-shifted carrier PWM (PSPWM), which can keep the capacitor voltage being balanced by applying the same time of the charging and the discharging switch states [4]. But the harmonic performance of output voltage with PSPWM is poor, especially under low modulation index region. For many of these applications, flying capacitor multilevel inverters will operate in the low amplitude modulation index region, such as static var compensation, motor drives, and active power filters.

Many large variable speed drives operate the majority of the time at just a fraction of their rated loads. Static var generators and active filters may also operate for long durations well below their rated capabilities, such as at night when the production has stopped at a commercial or industrial facility [5]. The multilevel inverters that are the backbone of these products have to be sized for the largest rated loads that will be demanded of them; however, they also should be optimized to operate proficiently over most of their operating regions including at low amplitude modulation index. The paper presents a novel PWM method for flying capacitor multilevel inverters, which improves the harmonic performance of output voltage, especially under low modulation index region.

* Corresponding author. Tel.: +86-516-8389-2513.
E-mail address: miao0124@163.com.

1878-5220/09/$– See front matter © 2009 Published by Elsevier B.V.
doi:10.1016/j.proeps.2009.09.240

2. Principle

2.1. Principle of flying capacitor three-level inverters

As shown in Fig.1, a flying capacitor three-level inverter leg consists of two switching cells, $S1/D1$ and $S4/D4$ clamped by the dc link together with the clamping capacitor work alternatively forming the first switching cell, while $S2/D2$ and $S3/D3$ clamped by the clamping capacitor work alternatively forming the second switching cell. To maintain a steady state stability of the clamping-capacitor-voltage, the instantaneous duty cycles of the two switching cells must be equal to each other [4]. Output voltage and switch sequence for four switch states of flying capacitor three-level inverters are listed in Table 1. Assumed that the load is inductive and the current flows to the load, the switch state “0+” charges the flying capacitor and switch state “0-” discharges it. Consequently, if the approval time of two switch states is identical in some period, we can maintain the voltage of flying capacitor $V_{dc}/2$ as an average.

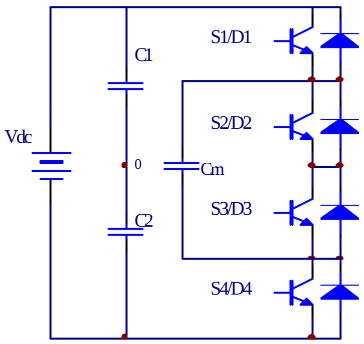

Fig. 1. Structure of a half-bridge flying capacitor three-level inverter

Table 1. Output voltage and switch sequence for switch states of flying capacitor three-level inverter

Output voltage	Switch state	Switch sequence			
		Sa1	Sa2	Sa3	Sa4
Vdc	1	1	1	0	0
Vdc/2	0+	1	0	1	0
	0-	0	1	0	1
0	-1	0	0	1	1

2.2. Principle of novel carrier-based PWM method with voltage balance for flying capacitor multilevel inverters

In order to improve the harmonic performance of output voltage under low modulation index region, the paper presents a novel carrier-based PWM method for flying capacitor multilevel inverters. The carrier of the proposed method is shown in Fig.2 where the solid line is the carrier1, which corresponds to switch S1; the dashed line is carrier2, which corresponds to switch S2. According to the reference voltage, the new carrier can be separated into two parts (in case the reference voltage is between Vdc/3 and Vdc, in case the reference voltage is between 0 and Vdc/3), the two parts are chosen depending on the magnitude of the reference voltage.

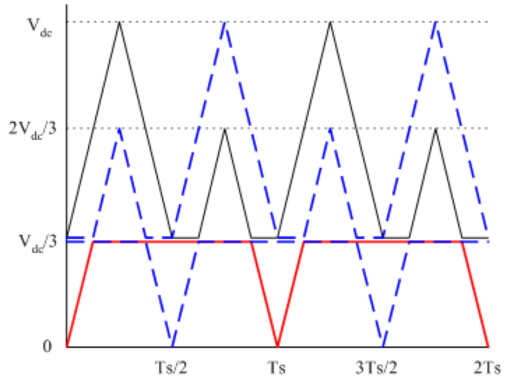

Fig. 2. Novel carrier for flying capacitor three level inverters of the proposed PWM method

Fig.3, Fig.4, and Fig.5 show the reference, the carrier, gate signal of S1 and S2 and corresponding switch states when reference voltage is between 0 and Vdc/3, between Vdc/3 and 2Vdc/3, and between 2Vdc/3 and Vdc, respectively. The gate signal of S1named Gs1 comes from the comparison between the reference and the carrier1 and the gate signal of S2 named Gs2 comes from the comparison between the reference and the carrier2. When reference voltage is between 0 and Vdc/3, as shown in Fig.3, the switching states are shown in the order of "-1"-"0+"-"-1"-"0-"-"-1". It can be seen that during time of switch state "0-" and switch state "0+" is equal to 2d, therefore, the voltage of flying capacitor can keep balance in Ts. When reference voltage is between Vdc/3 and 2Vdc/3, as shown in Fig.4, the order of switching states are shown as "1"-"0-"-"-1"-"0-"-"1"-"0+"-"-1"-"0+"-"1", and it can be seen that during time of switch state "0-" and switch state "0+" both is equal to d2-d1, therefore, the voltage of the flying capacitor can keep balance in Ts. When the reference voltage is between 2Vdc/3 and Vdc, as shown in Fig.5, the switching states are shown as "1"-"0-"-"1"-"0+"-"1" order, and it can be seen that during time of switch state "0-" and switch state "0+" both is equal to Ts-2d, therefore, the voltage of the flying capacitor can keep balance in Ts.

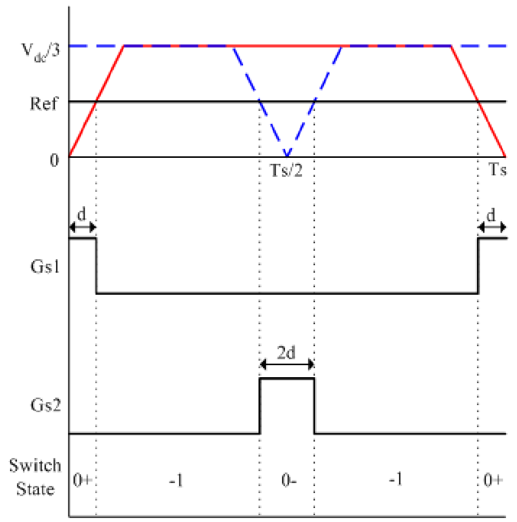

Fig. 3. The principle of voltage balance of flying capacitor with proposed PWM in case the reference voltage is between 0 and Vdc/3

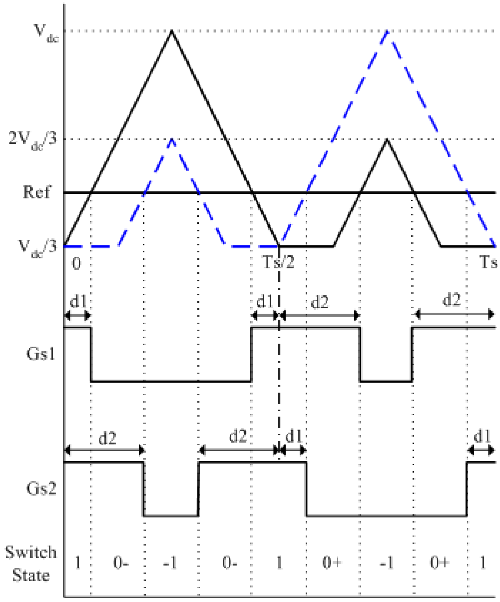

Fig. 4. The principle of voltage balance of flying capacitor with proposed PWM in case the reference voltage is between Vdc/3 and 2Vdc/3

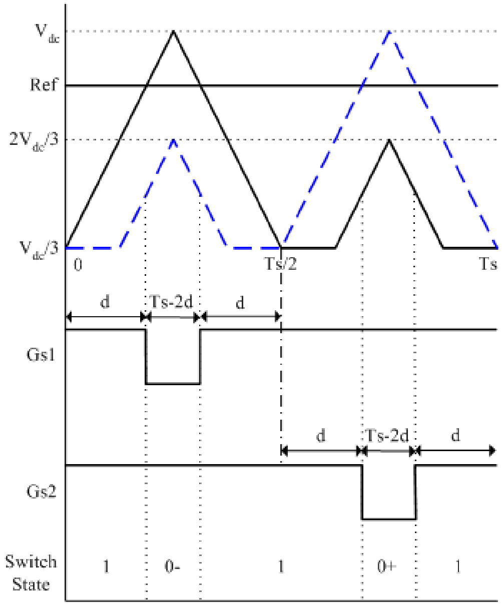

Fig. 5. The principle of voltage balance of flying capacitor with proposed PWM in case the reference voltage is between 2Vdc/3 and Vdc

From above analysis, it can be seen that the charge and discharge time of the flying capacitors are the same in a Ts with the proposed PMW method for flying capacitor multilevel inverters.

3. Experimental

In order to verify the validity of the proposed PWM method, the experiments for a three-level inverter are carried out. A medium power three-level inverter is established in the lab, with the DC bus voltage being 400V and the switching frequency being 3KHz. The proposed PWM method for three-level inverter is realized by DSP TMS320F240 and FPGA. Fig.6, Fig.7 and Fig.8 show the experimental phase-voltage, line-voltage switched waveforms, current waveforms, and experimental spectrum of line-voltage waveforms of proposed PWM method under modulation index 0.8, respectively. Fig.9, Fig.10, and Fig.11 show the experimental phase-voltage, line-voltage switched waveforms, current waveforms and experimental spectrum of line-voltage waveforms of proposed PWM method under modulation index 0.3, respectively. The coincidence of simulated and experimental results confirms the rightness and practicality of the proposed PWM method. Fig.12 shows the measured curves of line voltage THD against modulation index of three-level inverter with proposed PWM and PSPWM. It is evident that the characteristics of the proposed PWM method are better than the conventional PSPWM for flying capacitor three-level inverters, especially under low modulation index. Table.2 shows the THD (below the 150^{th} harmonics) of the three-level inverter unfiltered line-voltage switched waveform.

Table 2. Measured THD of the PWM methods for the three-level inverter under high modulation index and low modulation index

Mod index	PWM method	
	The proposed PWM	PSPWM
0.8	36%	59%
0.3	43%	134%

In order to verify the applicability of the proposed PWM methods to flying capacitor multilevel inverters (five level or higher level inverter), the simulations of the proposed PWM method for flying capacitor five level inverters are carried out, the DC bus voltage is 400V, and switching frequency is 1025 Hz. Fig.13 shows the simulated curves of line voltage THD against modulation index of five-level inverter with proposed PWM and PSPWM. It is evident that the performance of the proposed PWM method is better than the conventional PSPWM for the flying capacitor multilevel inverters.

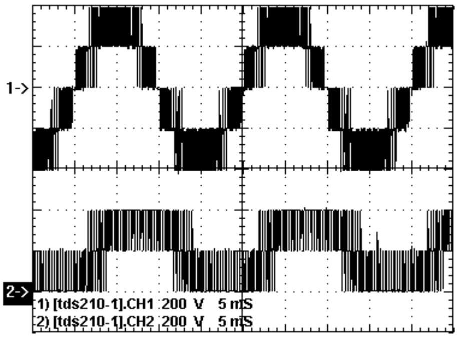

Fig. 6. Experimental waveform of phase-voltage and line-voltage with proposed PWM for flying capacitor three level inverter with Mi = 0.8

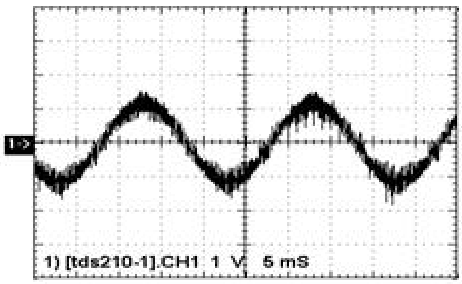

Fig. 7. Experimental current waveform with proposed PWM for flying capacitor three level inverter with Mi = 0.8

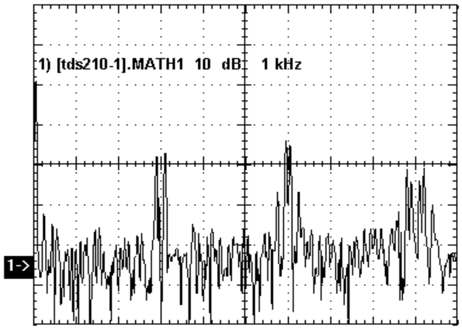

Fig. 8. Experimental spectrum of line-voltage with proposed PWM for flying capacitor three level invert er with Mi = 0.8

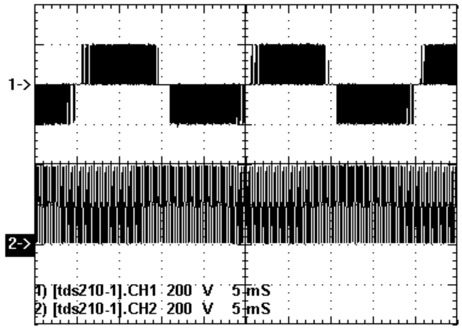

Fig. 9. Experimental waveform of phase-voltage and line-voltage with proposed PWM for flying capacitor three level inverter with Mi = 0.3

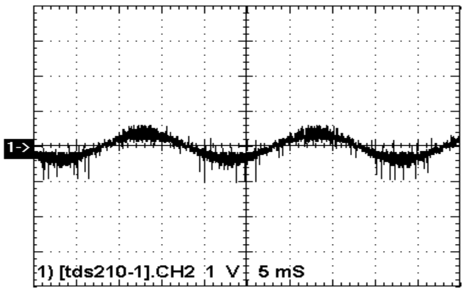

Fig. 10. Experimental current waveform with proposed PWM for flying capacitor three level invert er with Mi = 0.3

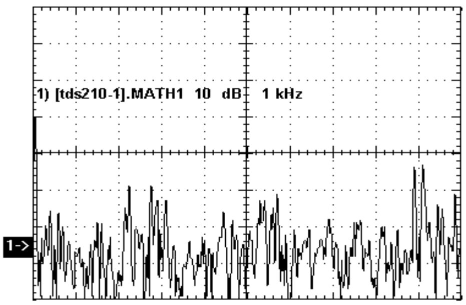

Fig. 11. Experimental spectrum of line-voltage with proposed PWM for flying capacitor three level inverter with Mi = 0.3

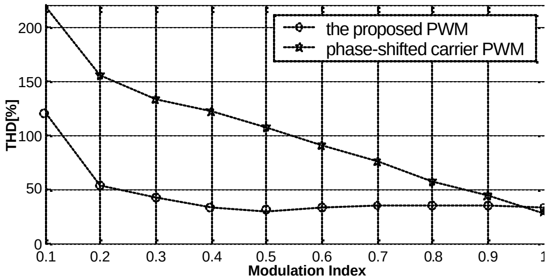

Fig. 12. Measured curves of line voltage THD against modulation index of three-level inverter with proposed PWM and PSPWM (below the 150th harmonics)

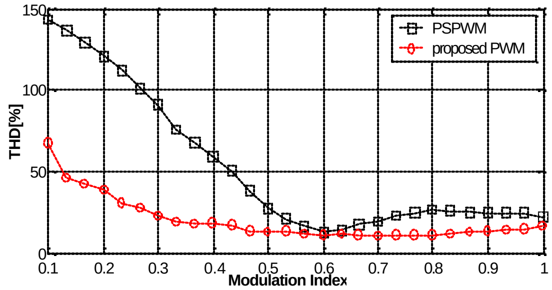

Fig. 13. Simulated curves of line voltage THD against modulation index of five-level inverter with proposed PWM and PSPWM (below the 150 th harmonics)

4. Conclusions

In this paper, a novel carrier-based PWM method for flying capacitor multilevel inverters is proposed, the proposed PWM method for flying capacitor multilevel inverters exhibit good performance under both high and low modulation index regions. The novel PWM method balances flying capacitor voltage in a period. The simulation and experimental results for a three-level inverter and simulation results for a five-level inverter under high and low modulation indexes verify the proposed PWM method.

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