Comparing the Phase-Shifted and Level-Shifted PWM Techniques for Multilevel Flying Converters

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Abstract: This paper evaluates the performance of two common carrier-based techniques to control the voltage of the flying capacitor multi-level inverter (FC_MLI). These two techniques are Phase shifted Pulse Width Modulation (PS-PWM), and Level shifted Pulse Width Modulation(LS-PWM). First, the structure of FC-MLI is studied. Also, the principle of operation of PS-PWM and LS-PWM are explained. Then using the PSIM simulation software a three-level and five-level flying capacitor inverters are simulated. The effect of PS-PWM and LS-PWM on 3 levels and 5 level FCI performance is investigated. The time-domain simulation and harmonic analysis results indicate that the PS-PWM has a better performance than the LS-PWM. Also, these results show that increasing the voltage level in the flying capacitor structure decreases the voltage and current harmonics.

Keywords: 3 to 6 keywords must be supplied.

1. Introduction

In recent years with increasing the capacity of renewable systems, the output power of these sources has been increased. Then we need a new generation of inverters to convert this high-level dc voltage to high-level ac voltage[1]. Therefore the idea of the multilevel inverter has attracted attention recently [2]. In addition to renewable power plants, these converters are also used in other high voltage industries, including industrial drives [3]. So far, different types of multilevel Inverter have been introduced, which the most common of them are: diode clamped multi-level inverter (DCMLI), cascade multi-level inverters (CMLI), and flying capacitor multilevel inverters (FCMLI)[4].

DCMLI, by using the clamping diodes, reaches the desired voltage level. The main advantage of this structure is the low stress on the power electronic switches. The main drawback of this topology is the difficult control for achieving the balanced neutral point. DCMLI topology has a modular topology. Therefore, it has good reliability, the main drawback of this structure is that for generating a high voltage level, many dc sources are required[5]. The FCMLI has a similar structure to the DCMLI, but clamping capacitors are used instead of clamping diodes. The main advantage of this structure compared to the DCMLI is that there are several switching combination structures for any particular voltage level, charging and discharging of clamping capacitors in each switching combination, providing a natural balancing voltage[4].

The number of output voltage levels in FCMLI depend on the number of clamping capacitors, the number of power electronic switches, and the switching method. Usually, the sine-triangle PWM techniques are used in FCMLI. Sine-triangle PWM techniques include the phase level PWM (PL-PWM) and phase-shifted PWM (PS-PWM)[6]. In this paper, to select the optimal switching method, we analyzed the performance of three-level and five-level FCMLI for these two switching methods.

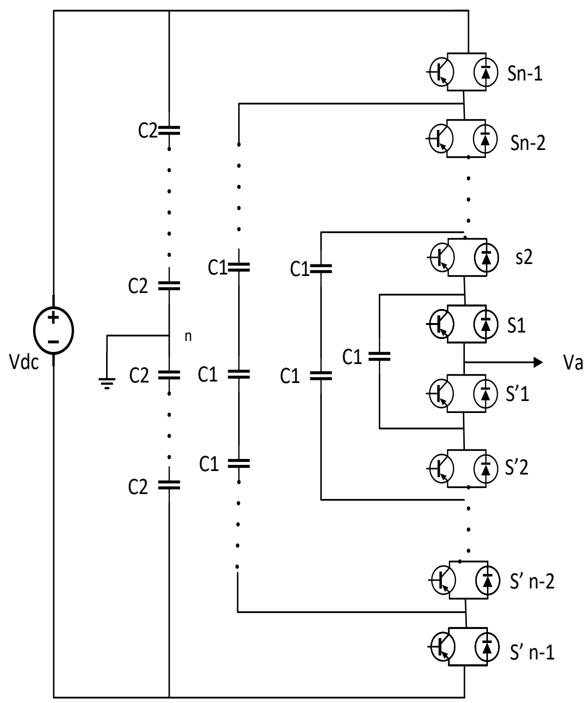

Fig 1*- Block Diagram of N level Flying Capacitor*

2. MultiLevel Flying Capacitor Inverter

2.1. General Structure

Fig.1 shows the general structure of a single-phase n-level flying capacitor inverter. Based on this figure, each phase of an n-level flying capacitor inverter (FCI) consists of $a\ (n-1)\times(n-2)$ clamping capacitor, (n-1), considering Vdc as the main capacitor connected to the main capacitor,connected to the dc link. This Inverter also has 2(n-1) power electronic switches.
The corresponding switches on the upper and lower legs have a complementary manner. By assuming the same size for clamping capacitors, the voltage of each clamping capacitor is $v_{dc}/(n-1)$, and the stress voltage of each semiconductor switch is equal to $v_{dc}/(n-1)$. A three-phase n-level flying capacitor has three legs with a similar structure connected to the dc-link[4].

2.2. Three Level Flying Capacitor Inverter

The three-phase, three-level flying capacitor generates a three-phase voltage with three levels. Table 1 shows the different switching states and their associate voltages. TABLE1 indicates that there are two repetitive switching modes for generating zero output voltage. If switches S1 and S'1 are in the on position, capacitor C1 is charged, and when switches S2 and S'2 are in the on position, capacitor C1 is discharged.

TABLE 1- SWITCHING STATES OF 3 LEVEL FCI

Switching State: S'2	S'1	S2	S1	Van
OFF	ON	OFF	ON	OFF
ON	OFF	ON	OFF	OFF
OFF	OFF	ON	ON	Vdc/2
ON	ON	OFF	OFF	-Vdc/2

2.3. Five Level Flying Capacitor Inverter

Five-level FCI has four switches, which provide 16 switching states shown in TABLE2. Table 2 indicates that in 5 levels FCI, there are four redundant switching combinations for generating -Vdc/4 and Vdc/4, and six redundant states for generating 0 Volt.

TABLE2- *Switching states of 5 level FCI*

Switching State S'4	S'3	S'2	S'1	S4	S3	S2	S1	Van
OFF	OFF	OFF	OFF	ON	ON	ON	ON	Vdc/2
OFF	OFF	OFF	ON	ON	ON	ON	OFF	Vdc/4
OFF	OFF	ON	OFF	ON	ON	OFF	ON	
ON	ON	OFF	OFF	OFF	OFF	ON	ON	
OFF	OFF	OFF	ON	OFF	ON	ON	ON	
ON	ON	OFF	OFF	OFF	OFF	ON	ON	0
OFF	ON	OFF	ON	OFF	ON	OFF	ON	
ON	OFF	OFF	ON	OFF	ON	ON	OFF	
OFF	ON	ON	OFF	ON	OFF	OFF	ON	
OFF	ON	OFF	ON	ON	OFF	ON	OFF	
OFF	OFF	ON	ON	ON	ON	OFF	OFF	
OFF	ON	ON	ON	ON	OFF	OFF	OFF	_Vdc/4
ON	OFF	ON	ON	OFF	ON	OFF	OFF	
ON	ON	OFF	ON	OFF	OFF	ON	OFF	
ON	ON	ON	OFF	OFF	OFF	OFF	ON	
ON	ON	ON	ON	OFF	OFF	OFF	OFF	-Vdc/2

3. CARRIER BASED PULSE WITH MODULATION TECHNIQUE

Usually, multi-level inverters use carrier-based PWM techniques. This method compares a reference signal with multi-carrier signals. The reference signal is a sinusoidal waveform, and the carrier signals are generated by shifting the phase or the Level of a triangular waveform.

3.1. Phase Shifted SPWM

An N-level PS-PWM Inverter consists of (N-1) carrier signals. For generating the switching pattern of the upper arm switches, these carrier signals are compared with positive sinusoidal reference signals. In the lower arm switches, these carrier signals are compared with the negative sinusoidal reference signal[7]. The carrier signals have the same frequency, the same amplitude, and the same dc-offset, but the phase angle of each carrier signal (θ_c) is:

$$\theta_C = \frac{n\times\pi}{(N-1)}\ ,\ \ n = 1,2,\dots,(N-1). \qquad (1)$$

Therefore, as shown in Fig.2-a, for a 3-level FCI, the phase angle of carrier signals are 0° and 90°, and for a 5-level FCI, these angles are, 45° and 135°.

3.2. Level Shifted SPWM

As shown in Fig.2-b, in the PL-PWM method for an n-Level converter, there are $(N-1)$ carrier signals for the upper arm[8]. These carriers have the same frequency, phase angle, and amplitude, but various dc-offsets. These dc-offsets are:

$$dc_{offset} = \frac{\pm n}{(N-1)}\quad ,\quad n = 1,2,\dots,(N-1)/2. \qquad (2)$$

a 3-level FCI has two carrier signals in which dc offset of the first carrier signal is equal to 0.5, and dc offset of the second signal is equal to -0.5. (Fig2-b).) Similarly for a 5-level, FCI there are four carrier signals, whose dc offsets are: $0.25\ ,0.5,-0.25, and-0.5$. For the switching of the lower arm switches, these carriers are compared with the negative sinusoidal reference signals

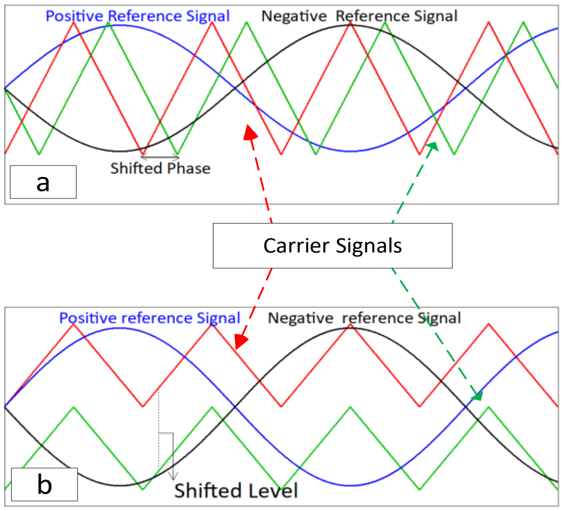

***Fig 2**- Carrier-based PWM a: PS-PWM, b: LS-PWM*

4. Case Study

To analyze and compare the performance of PS-PWM and PL-PWM, in this paper we applied these two methods on three-level and five level FCI inverters. Our study system consists of a 10-kW, and 400v dc power supply, which through a flying capacitor multilevel inverter is connected to the three-phase RL load, with $R = 10\ \Omega, L = 1.5\ mH$. Each electrolytic capacitor connected to the dc-link is 6 mF, and each clamping capacitor is 200µF. The device type is IGBT F4-50R06W1E3, its on-resistance is 0.01 Ω, and its off resistance is 2E6Ω. In both PWM techniques, the fundamental frequency is 50 Hz, the carrier frequency is 5 kHz, and the modulation index is 0.95.

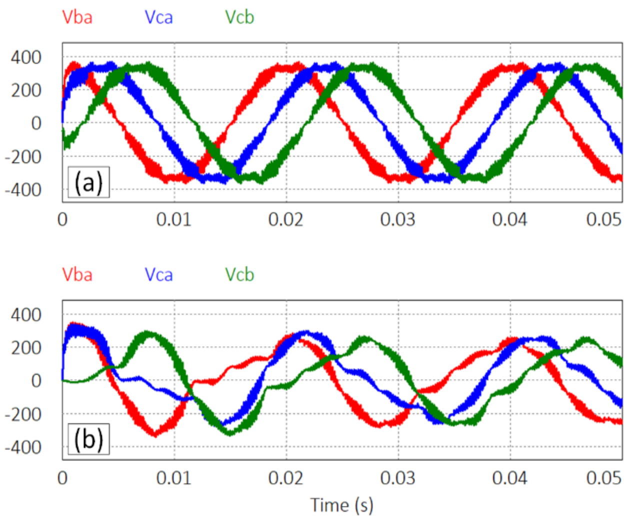

Fig 1-The output voltage of 3level FCI with a) PS-PWM, b) LS-PWM

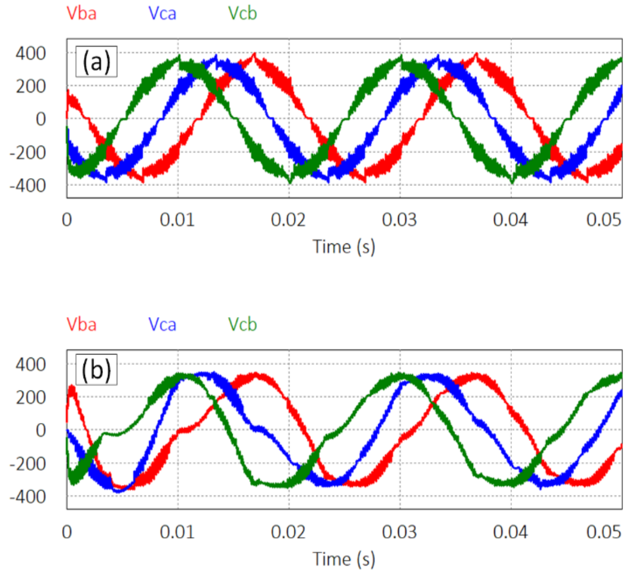

Fig 2- The output voltage of 5level FCI with a) PS-PWM, b) LS-PWM

4.1. Time Domain Results

Fig3-a and b show the line-to-line voltages for three-level FCI with phase-shifted PWM technique and Level- Shifted PWM technique, respectively. Based on this figure, the phase-shifted PWM technique performs better than the Level-shifted PWM.

The lin-to-line voltages for five-level FCI with PS-PWM and LS-PWM are presented in Fig.4. This figure similarly indicates that PS-PWM is better than LS-PWM. Also, comparing the results of Fig.3 and Fig.4 shows the output voltage of a five-level converter is more uniform than a three-level converter.

Fig. 5 and 6 show the output current of three-level and five-level FCI. Comparing these figures indicates that the current of 5-level has less harmonic than the 3-level ones. Also, the phase-shifted PWM technique has a better performance in both of these inverters.

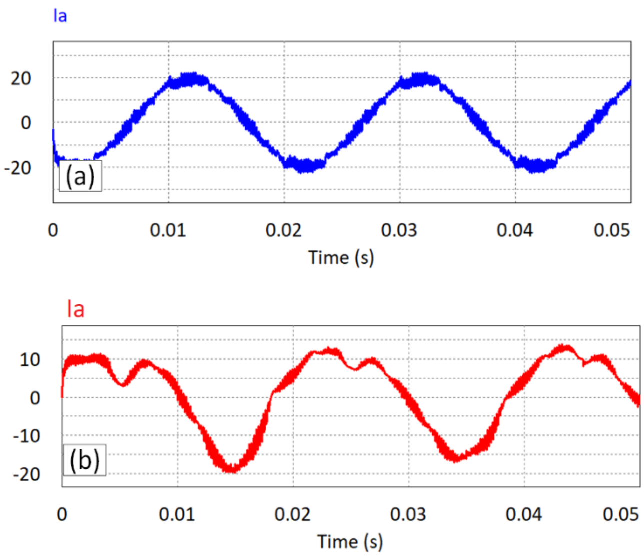

Fig5. The output current of 3level FCI with: a) PS-PWM, b) LS-PWM

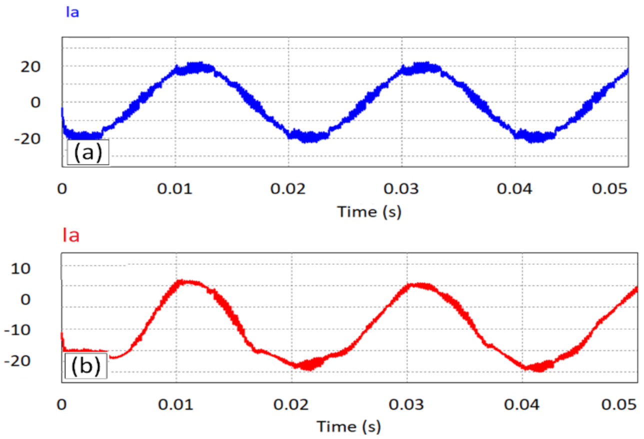

Fig6- The output current of 5level FCI with: a) PS-PWM, b) LS-PWM

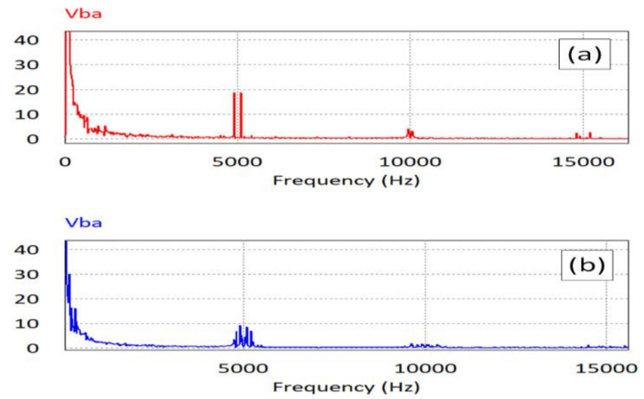

Fig7- harmonic spectrum of the output voltage of 3level FCI with a) PS-PWM, b) LS-PWM

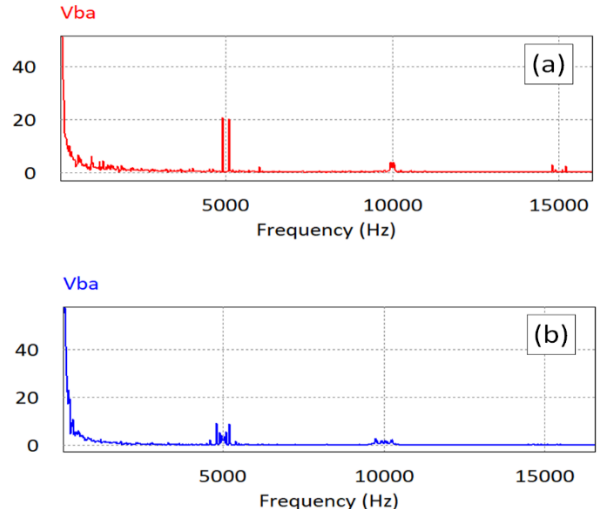

Fig8- Harmonic spectrum of the output voltage of 5level FCI with a) PS-PWM, b) LS-PWM

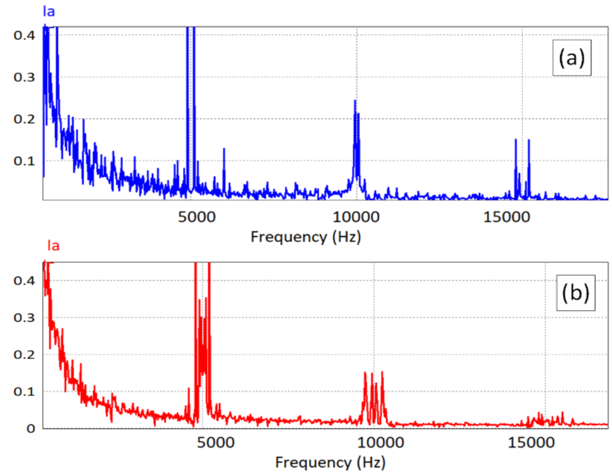

Fig9- Harmonic spectrum of the output Current of 3level FCI with a) PS-PWM, b) LS-PWM

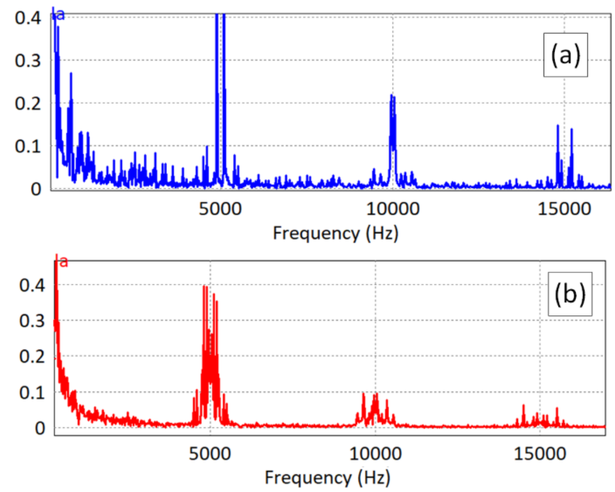

Fig 10- Harmonic spectrum of the output Current of 5level FCI with a) PS-PWM, b) LS-PWM

4.2. Harmonic Analysis

To more accurate comparison of PS-PWM and LS-PWM techniques, we calculate the harmonics of voltage and current using the fast Fourier transform (FFT). Fig.7 and fig.8 show the harmonic of line to line voltage for the 3-level and 5-level FCI, respectively. This figure indicates that the main voltage harmonics are around the switching frequency (5000Hz) and its multiples. The amplitude of the voltage harmonics of the 5 level is more than the 3level. Also, the LS-PWM technique has larger harmonic components in both of these converters. Fig.9 and 10 show the harmonic output current for 3-level and 5-level inverters. This figure indicates that similarly, the inverter's harmonic components with LS-PWM are larger than the PS-PWM.

To investigate the accuracy of the results of FFT analysis, we also calculate the total harmonic distortion (THD) of output voltage and output current. Table3 shows these values, considering that the fundamental frequency equals 50Hz. According to this TABLE in 3 level FCI, the voltage THD of the LS-PWM technique is equal to 0.4957, and this amount for the PS-PWM technique is 0.132. Similarly, the current THD for PS_PWM and LS-PWM is 0.483, and 0.164, respectively. Comparing the second and third rows of this table clearly indicates that 5 level FCI has less harmonic than the 3-level FCI.

Table 3- Voltage and Current THD in 3 and 5 Level Flying Capacitor

	THD of Output Voltage		THD of Output Current	
	LS-PWM	PS-PWM	LS-PWM	PS-PWM
3 Level	0.4957	0.1324	0.483	0.164
5-Level	0.2705	0.1035	0.357	0.113

5. CONCLUSION

This paper studied the phase-shifted PWM and Level Shifted PWM techniques. These two switching methods are applied on the three-level and five-level flying capacitor inverter, and the system's performance has been discussed. These investigations include the time-domain simulation, FFT analysis, and total harmonic distortion calculations. In this study, the fundamental frequency is equal to 50 Hz, and the switching frequency for both the PS-PWM and LS-PWM is 5kHz. The results of both time-domain studies show that in both 3-level and 5-level inverters, the quality of output voltage and output current of inverter with PS-PWM technique is higher than the LS-PWM. Also, based on the harmonic analysis in both 3-level and 5-level structures, the THD of output voltage and output current of the system with LS_PWM is more than the PS-PWM. It has been found that the harmonic analysis results verify the results of time-domain simulations.

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