Simulation Study of the Carrier-Based PWM Method in Three-Phase Flying Capacitor Inverters

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Abstract ***– This paper is a simulation study of modulation strategies in three-phase flying capacitor inverters. Under investigation are those strategies that solve the capacitor voltage balancing problem: phase-shift PWM method, the saw-tooth rotation PWM method and carrier redistribution PWM method. The results are shown through simulation.***

Keywords: ***phase-shift PWM method, the saw-tooth rotation PWM method, carrier redistribution PWM method, cascade multilevel PWM inverter, flying capacitor inverter.***

I. INTRODUCTION

Recently, multi-level inverter is being concerned as a topology for high voltage and high power of inverter system. In case of N-level, it can enlarge the capacity of the power conversion device by increasing the voltage by (N-1) times compared to conventional 2-level inverter, with more voltage level than 2-level inverter, which is much more sinusoidal output voltage waveform, and consequently decrease harmonics and EM1 phenomenon.
There are three kinds of multi-level inverters (neutral point clamped inverter, cascade inverter, flying capacitor inverter) and nowadays neutral point clamped (NPC) inverter is most commonly used. But diode clamped inverter has much difficulty in controlling each capacitor voltage constituting DC-link to balance beyond 4-level. And it is difficult to apply to high-level system structurally, since the number of additional clamping diode increases by (N-1)*(N-2) per phase when the clamping diodes with the same voltage and current rating are used. On the other hand, flying capacitor defects to need additional capacitors, and require control of capacitor voltage like a diode clamped inverter. But these capacitors may have smaller than DC-link capacitor in capacity.
The flying capacitor inverter have many attractive properties for medium voltage applications, including in particular the advantage of transformerless operation, and the ability to naturally maintain the cell capacitor voltages at their target operating levels [1]. This property is called natural balancing, and allows in principle the construction of such inverters with a large number of voltage levels. The flying capacitor (or multicell) inverter, shown in Fig. 1(a), uses a series connection of "cells" comprising a flying capacitor and its associated complimentary switch pair, and produces a switched.
The proposed model for study of the carrier-based PWM method in three-phase flying capacitor inverters is based on inverter switching function rather than actual circuit configuration. This model will be used for harmonic analysis of the output voltage of the inverter for different PWM strategies. The analyzed PWM strategies are those which allow the voltage balancing of flying capacitors.

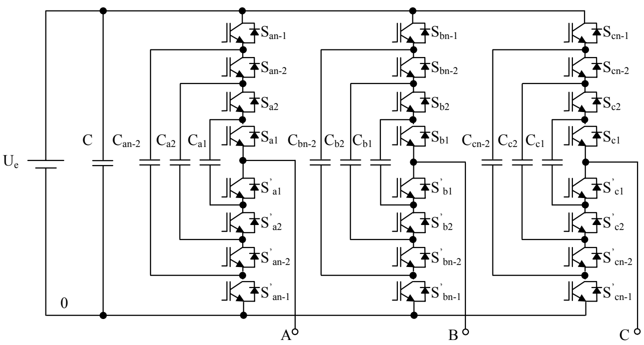

Fig. 1 Circuit diagram of an *n* level flying capacitor inverter

II. FLYING CAPACITOR MULTILEVEL INVERTER

An inverter leg may be represented as in Fig. 2. Depending on the adjacent switching states of the capacitor, the current through, for example, C_{xk}, is i_x when S_{xk+1} and S'_{xk} are in ON state, $-i_x$ when S'_{xk+1} and S'_{xk} are in ON state or zero when S_{xk} and S_{xk+1} are in ON state or when S'_{xk} and S'_{xk+1} are in ON state. Consequently, adequate driving of the adjacent transistors can modulate the current through C_{xk}.

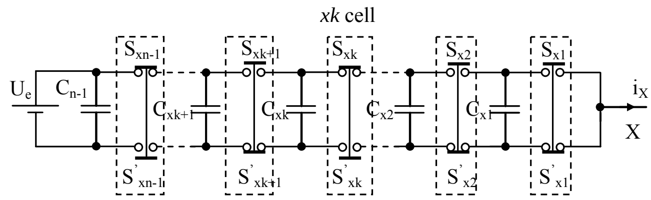

Fig. 2 Inverter leg of flying capacitor multilevel inverter.

Will say that two transistors S_{xk} and S'_{xk} form a switching cell xk, with $x \in \{a, b\}$, k=1...*n*-1. For the *n* level flying capacitor inverter there will be *n*-1 switching cells. Let us define the connection functions y_{xk} for each switching cell. For example, for the xk cell from Fig. 2, y_{xk}=1 when S_{xk} is in ON state, and $y_{xk}=0$ when S_{xk} is in OFF state. The current through C_{xk}, which depends on the connection functions is [2]:

$$i_{Cxk}=(y_{xk}-y_{xk+1})i_X\,,\ x\in\{a,\,b\},\ k\in\{1...n\text{-}1\}. \qquad (1)$$

The mean value of the voltage on capacitor C_{xk} will be maintained constant on switching period T_p if the mean value of current through capacitor is zero:

$$\int_0^{T_P} i_X\,(y_{xk}-y_{xk+1})dt=0 \Rightarrow \int_0^{T_P}(y_{xk}-y_{xk+1})dt=0 \qquad (2)$$

Relation (2) is accomplished if y_{xk} and y_{xk+1} have equal durations for each time period T_p. Obtaining the equal durations of all connection functions of commutation cells for an inverter leg is possible by using *n*-1 carrier signals with a $T_p/(n\text{-}1)$ phase shift between them, or by using carrier redistribution PWM method or the saw tooth rotation PWM method [3 – 6].

The expression of phase voltage for flying capacitor *n* level inverters depend on connection functions is [7]:

$$u_{X0}=y_{xn-1}u_{Cxn-1}+ \\ +\sum_{k=1}^{n-2}(y_{xk+1}+y_{xk})[(1-y_{xk+1})+(1-y_{xk})](-1)^{(1-y_{xk})}u_{Cxk} \qquad (3)$$
$$X=\{A,B,C\};\ x=\{a,b,c\}.$$

III. PWM METHODS FOR VOLTAGE BALANCING FOR FLYING CAPACITOR

From (2) the average variation of the flying capacitor voltage becomes zero when the time lengths of two adjacent connection functions are equal. This can be realized for the PWM modulation strategies for four level flying capacitor inverter as shown in the next three situations that depend on the positions of carrier signals [5], [6].

A. Phase Shifted PWM Method

In this case for the n level flying capacitor the n-1 carrier signals are phase shifted by $T_P/(n\text{-}1)$.

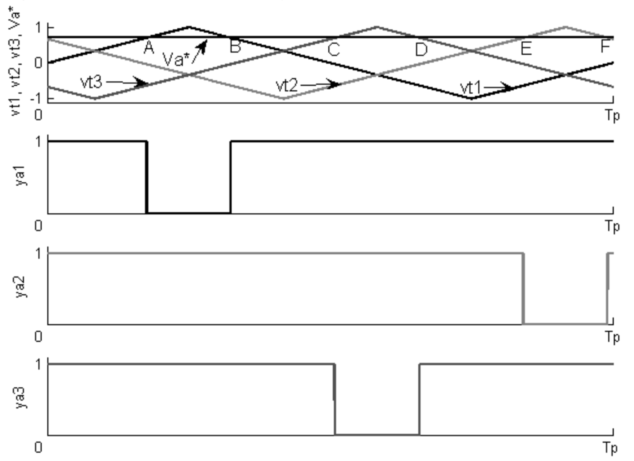

Fig. 3 Phase shift PWM for four level flying capacitor inverter.

Fig. 3 presents the carrier signals, modulator signal and connection functions for four level capacitor flying inverter for one leg. In this case there are three carrier signals: vt1, vt2, vt3 and three connection functions y_{a1}, y_{a2} and y_{a3}. Va* is the modulator signal and it is assumed constant for switching time T_p.

In Fig. 3 the segments AB, CD and EF have the same length. The length of these segments correspond to the time in which the connection functions yields the zero value. Therefore, for this modulation type the time lengths of connection functions are equal and voltage balancing for flying capacitors is provided.

B. Saw-Tooth Rotation PWM Method

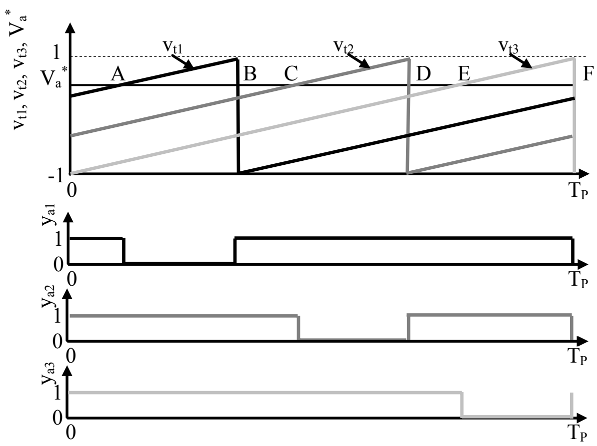

Fig. 4 Saw-tooth rotation PWM method for four level flying capacitor inverter.

Saw-tooth rotation PWM method presented in [4], [5] consists after all in using the (*n*-1) saw-tooth carrier signals phase shifted by $T_P/(n\text{-}1)$. In this case, like in the previous, the segments determined by cross point between carrier signals vt1, vt2, vt3 and modulator signal V_a^* are equal and voltage balancing for flying capacitors is provided.

C. Carrier Redistribution PWM Method

Carrier redistribution method is treated in [5], [6], [9]. Briefly, in this method for a switching cell, a sum of triangular and trapezoidal signals are used as carrier signal. For an *n* level flying capacitor one triangular signal and *n*-2 trapezoidal signals are used. The carrier signals are phase shifted by $T_P/(n\text{-}1)$.

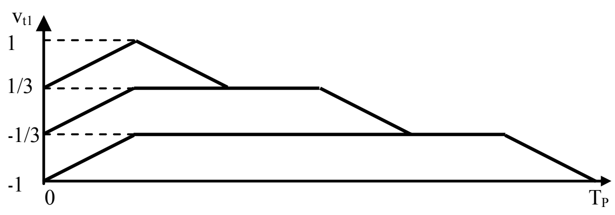

Fig. 5 Carrier signal for a switching cell when carrier redistribution PWM method are used.

When the modulator signal V_a^* crosses the carrier signals in [-1 -1/3] the connection functions are generated like in Fig. 6, when modulator signal V_a^* cross the carrier signals in [1/3 1] the connection functions are generated like in Fig. 7.

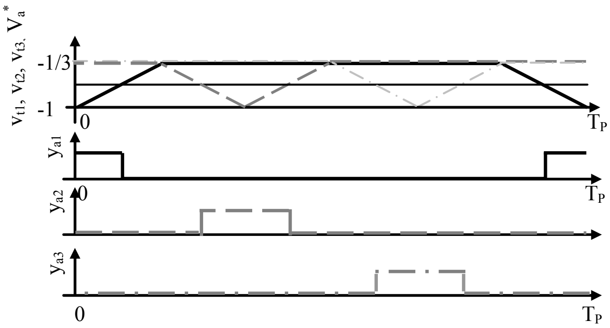

Fig. 6 Carrier redistribution PWM method for four level flying capacitor inverter when modulating signal is between [-1 -1/3].

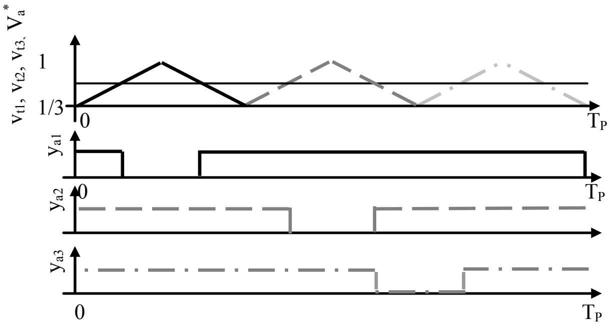

Fig. 7 Carrier redistribution PWM method for four level flying capacitor inverter when modulating signal is between [1/3 1].

From Fig. 6 and Fig. 7 it can be seen that the time lengths of the connection functions are equal and voltage balancing for flying capacitors is provided.

IV. SIMULATION RESULTS

The three methods presented above are analyzed with respect to their harmonic content and total harmonic distortion factor (THD).

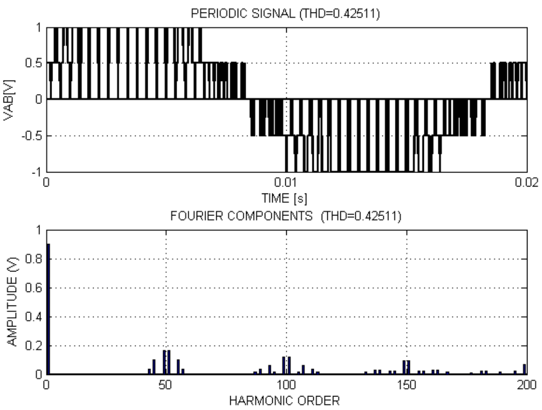

Fig. 8 Phase voltage and fourier components for three level flying capacitor inverter with phase shifted carrier signals.

The analysis is performed for three level and four level flying capacitor.

The carrier signals generated by *Triangle* block are like those presented in Fig. 3, Fig. 4 and Fig. 5 for the four level inverter. In the next figures the line voltage related to the DC link voltage and the amplitudes of harmonics are presented.

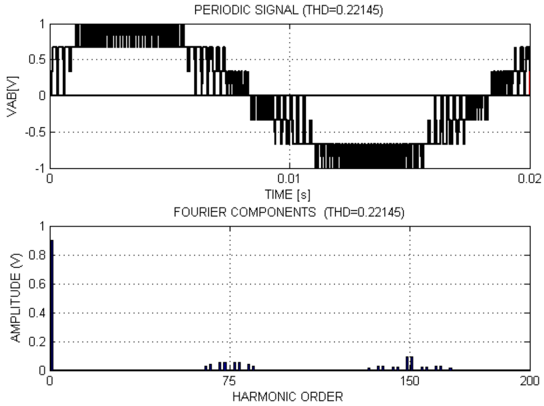

Fig. 9 Phase voltage and fourier components for four level flying capacitor inverter with phase shifted carrier signals.

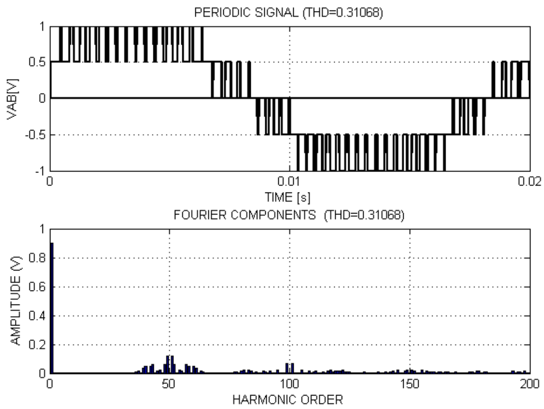

Fig. 10 Phase voltage and fourier components for three level flying capacitor inverter with saw-tooth rotation PWM.

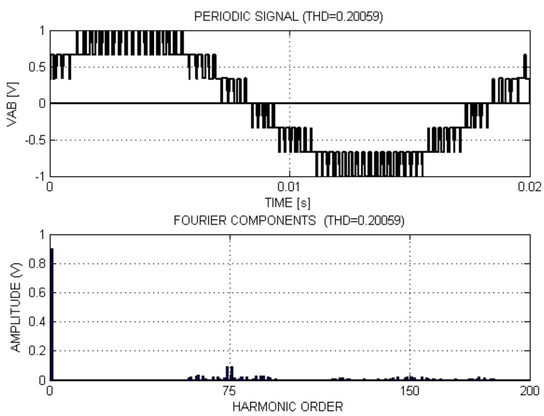

Fig. 11 Phase voltage and fourier components for four level flying capacitor inverter with saw-tooth rotation PWM.

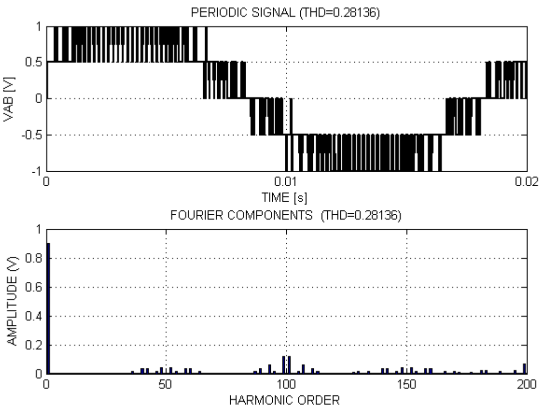

Fig. 12 Phase voltage and fourier components for three level flying capacitor inverter with carrier redistribution PWM.

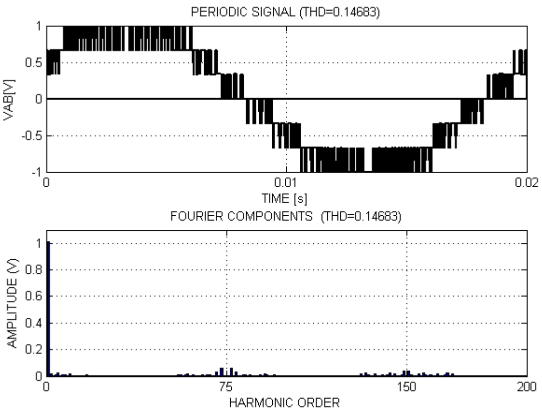

Fig. 13 Phase voltage and fourier components for four level flying capacitor inverter with carrier redistribution PWM.

The THD are calculated for the first 200 harmonics. The modulation index is 0.9 and switching frequency is 1250 Hz.

Three-phase reference signals are obtained by adding the offset voltage V_{off} to the original phase voltages to obtain an equivalent reference voltage. The offset voltage is defined as:

$$V_{off} = -\frac{[\max(V_a^* + V_b^* + V_c^*) + \min(V_a^* + V_b^* + V_c^*)]}{2} . \quad (4)$$

The THD values obtained by simulation using the presented model of the inverter for three and four level flying capacitor inverter for phase shifted PWM method (PSPWM), saw-tooth rotation PWM (STRPWM) and carrier redistribution PWM (CRPWM) are presented in Table 1.

TABLE I. THE THD VALUES OF LINE VOLTAGE

	3 level	4 level
PSPWM	0.425	0.221
STRPWM	0.281	0.200
CRPWM	0.285	0.146

From Fig. 8 to Fig. 13 we can see that the harmonic carrier bands appear at frequencies f_h given by:

$$f_h = k(n\text{-}1)f_p , \quad (5)$$

where k is an integer (k=1, 2, 3...), f_p is the frequency of carrier signal and n is the number of inverter levels.

From the three PWM methods the CRPWM allows one to obtain the lowest values of THD.

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