MULTIPHASE MULTILEVEL HYBRID CARRIER BASED SPACE VECTOR PWM ALGORITHM

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Abstract: This paper proposes a hybrid carrier based space vector modulation suitable for multiphase multilevel inverters. Multiphase multilevel inverters are controlled by this hybrid modulation to provide multiphase variable voltage and variable frequency supply. The proposed modulation combines the benefits of fundamental frequency modulation and carrier based space vector modulation strategies. The main characteristics of this hybrid modulation are the reduction in switching losses, and effectively improve harmonic performance. This algorithm can be applied to cascaded multilevel inverter topologies; it has low computational complexity and it is suitable for hardware implementations. The proposed modulation is developed based on PWM base generator and hybrid PWM control algorithm and it is implemented using TMS320F2407 DSP processor and Xilinx XC95108 CPLD controller respectively. The performance of this hybrid modulation is analyzed based on power loss, weighted total harmonic distortion, the linearity and it is compared with standard modulation strategies. Selected simulation and experiment results are reported to verify and validate the effectiveness of the proposed modulation technique.

Keywords: complex programmable logic device, digital signal processor, hybrid carrier based space vector modulation, multiphase multilevel inverter, weighted total harmonic distortion ,power loss analysis

1. Introduction

Multiphase machine drives have attracted considerable interest among researchers in recent years due to inherent advantages. Major advantages of using a multiphase machine are: improved reliability and increased fault tolerance; greater efficiency; higher torque density and reduced torque pulsations; lower per phase power handling requirements; enhanced modularity; improved noise characteristics[1].

Multilevel converter technology is based on the synthesis of a voltage waveform from several dc voltage levels. As the number of levels increases, the synthesized output voltage gets more steps and produces a waveform which approaches the reference more accurately. The major advantages of using multilevel inverters are: high voltage capability with voltage limited devices; low harmonic distortion; reduced switching losses; increased efficiency; good electromagnetic compatibility [2].Various multilevel converters structures are reported in the literature, and the cascaded multilevel inverter appears to be superior to other multilevel inverters in application at high power rating due to its modular nature of modulation, control and protection requirements of each full bridge inverter [3]. The power circuit for a five-phase five-level cascaded inverter topology is shown in fig.1 used to examine the proposed PWM technique.

Modulation control of multiphase multilevel inverter is quite challenging, and much of the reported research is based on somewhat heuristic investigations [4]-[5]. Most of the available work on PWM schemes for a multiphase voltage source inverter either covers carrier-based PWM or space vector PWM schemes. Space vector modulation (SVM) offers low harmonic distortion for three-phase inverters by placing the most unwanted harmonics power on triplen harmonics.

SVM is intrinsically a non-carrier-based digital technique for generating switching angles. However, due to constant sampling rate used in SVM, the equivalent carrier-based techniques have been developed. Carrier-based SVM is appropriate for inverters with more than five levels, where the computational overhead for conventional SVM is exceeding due to many output states [6].
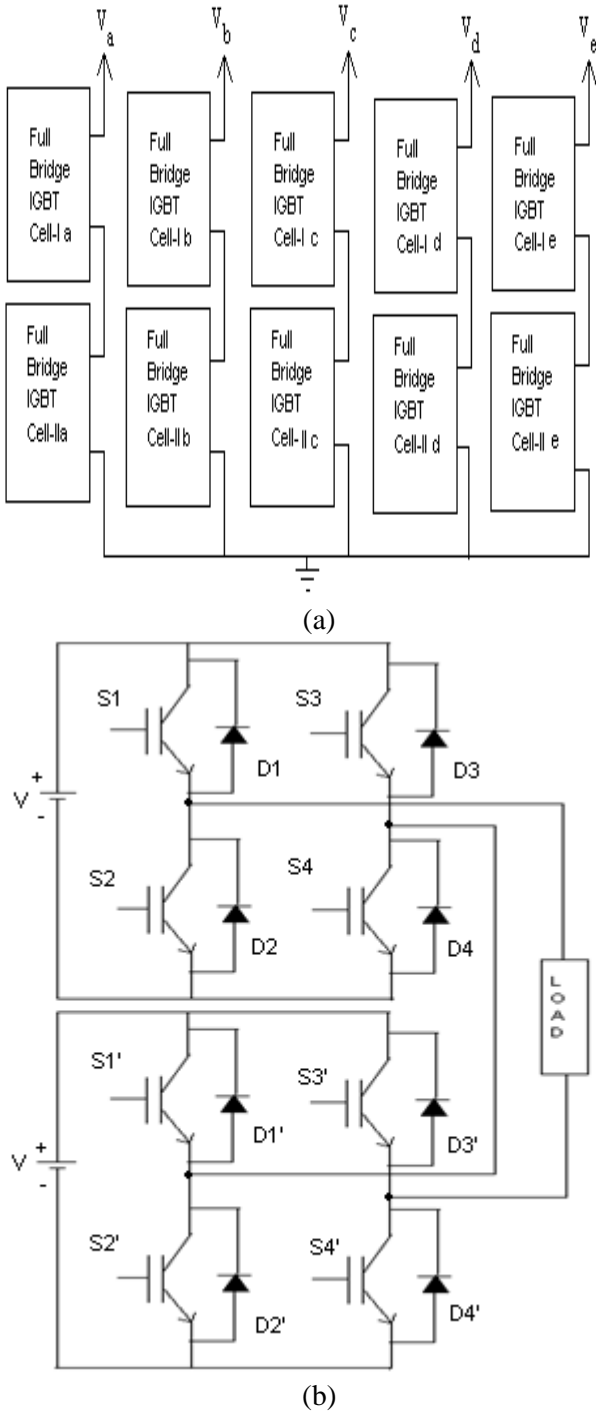
(a)

(b)

Fig.1. (a) Schematic diagram of the five phase inverter topology used to verify the proposed five-level hybrid CBSVM technique. (b) Power circuit configuration for one phase leg.

Wenxi Yao proposed carrier-based space vector modulation technique, which are harmonically equivalent, with the best spectral performance being achieved when the nearest three space vector states are selected with the middle two vectors centered in each half carrier switching interval [7]. This strategy is known as carrier based space vector modulation (CBSVM). Based on the literature, none of the authors have reported hybrid carrier based space vector modulation technique for a multiphase multilevel inverter.

In this paper, a new hybrid modulation technique is presented to address the reduction of power losses in multiphase multilevel inverter, with improved harmonic performance. The paper is organized in the following way. Section 2 describes the multiphase carrier based space vector modulation and development of hybrid modulation. Section 3 presents the harmonics and power loss analysis of multiphase multilevel inverter with this proposed modulation. Section 4 illustrates the simulation and experimental results of phase voltage and current waveforms including the discussion on the results. Finally, some conclusions are presented in section 5.
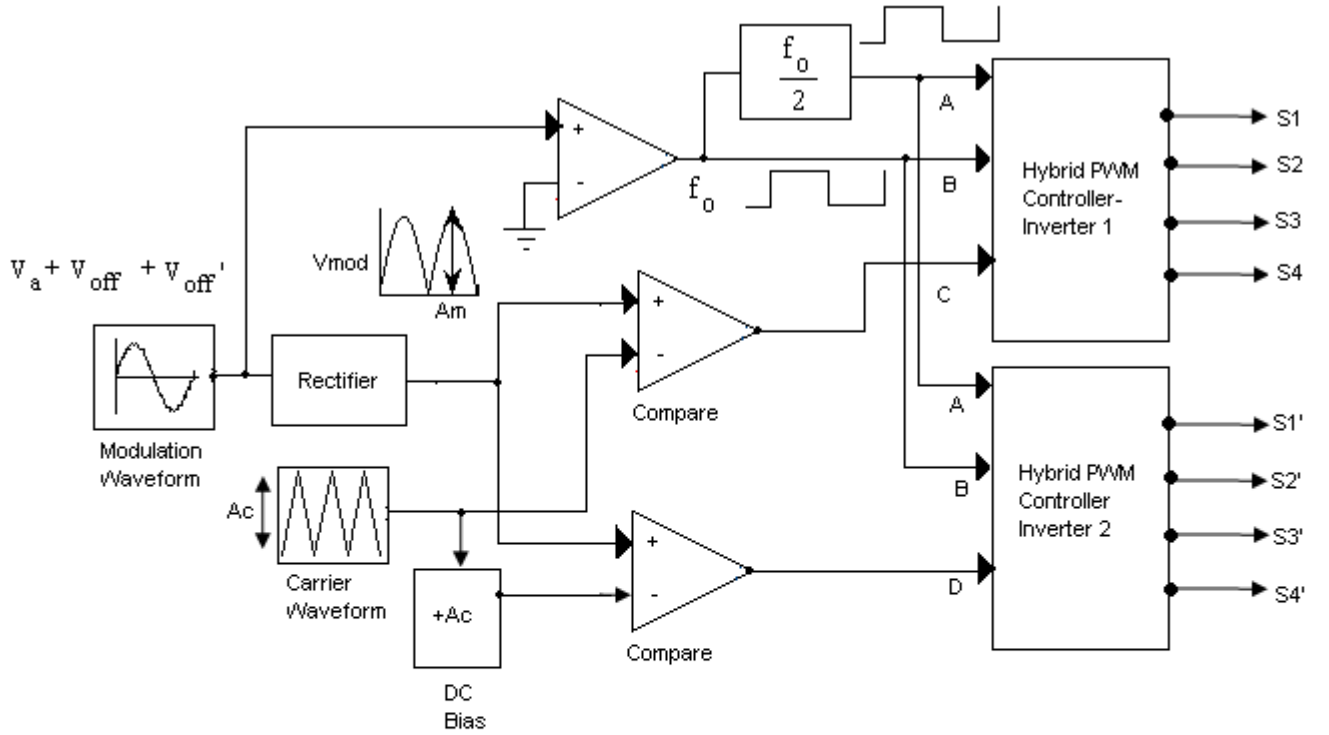
2. Hybrid PWM Algorithm Development

2.1 Multiphase Carrier Based Space Vector Modulation

Generally, carrier-based PWM of multilevel inverter can only select four switching-states at most, but SVM can select more. Selection of switching-states has more freedom in multilevel SVM than in multilevel carrier-based PWM. In order to solve that problem, multilevel SVM can also be decomposed into several two-level carrier-based PWM cells. This method effectively increases the number of switching in multilevel SVM scheme is more than in conventional PWM scheme, but the additional switching are mainly added in the area the modulated wave is steep, where output wave may be distorted most seriously, so it is more effective to improve the output voltage using multilevel SVM scheme than increasing frequency of carrier waves directly.

Carrier based space vector modulation (CBSVM) is derived from the addition of a common offset voltage to the multi-phase references will center the active space-vectors in the switching period, and hence match carrier modulation to get optimized space vector modulation. The offset voltage V_{off}' for multiphase multilevel operation can be calculated as:

$$V_{off} = -\frac{\max(V_a, V_b, V_c, V_d, V_e) + \min(V_a, V_b, V_c, V_d, V_e)}{2}$$

$$V_k' = (V_k + V_{off} + V_{dc}) \bmod (\frac{2V_{dc}}{N-1}), k = a, b, c, d, e$$

$$V_{off} = -\frac{max\,(V_a,V_b,V_c,V_d,V_e) + min\,(V_a,V_b,V_c,V_d,V_e)}{2}$$

$$V_k' = (V_k + V_{off} + V_{dc})\,mod\,(\frac{2\,V_{dc}}{N-1}),\ k = a,\,b,\,c,\,d,\,e$$

$$V_{off}' = \frac{V_{dc}}{N-1} - \frac{max(V_a',V_b',V_c',V_d',V_e') + min(V_a',V_b',V_c',V_d',V_e')}{2}$$

V_a, V_b, V_c, V_d, V_e- Phase reference Waveforms

Fig.2. Scheme of hybrid carrier based space vector modulation (One Phase leg)

$$V_{off}' = \frac{V_{dc}}{N-1} - \frac{max(V_a',V_b',V_c',V_d',V_e') + min(V_a',V_b',V_c',V_d',V_e')}{2}$$

Where V_{dc} is 1 p.u. The phase reference is then obtained by adding V_{off} and V_{off}' to the reference waveform $V_a, V_b, V_c, V_d,$ or V_e .Using the resultant reference and phase disposition carriers; the switching angles are then generated for multilevel inverter.

2.2 Multiphase Hybrid Carrier Based Space Vector Modulation

The proposed hybrid carrier based space vector modulation is the combination of fundamental frequency PWM and carrier based space vector modulation. The basic principle behind the proposed scheme, the four power devices in each full bridge module are operated at two different frequencies, two being commutated at the fundamental frequency of the output, while the other two power devices are pulse width modulated at CBSVM. This arrangement causes the problem of differential switching losses among the switches. This technique is optimized with sequential signal and the resultant hybrid CBSVM pulses overcome this problem. The general structure of the proposed system for one phase is shown in fig.2.

In this modulation strategy, three base PWM signals are required for each full bridge converter. A sequential signal (A) is a square signal with 50% duty ratio and it has half of the fundamental frequency. This signal makes every power switch operating at CBSVM and low frequency PWM

sequentially. Fundamental frequency PWM (B) is a square wave signal synchronized with the modulation waveform; B=1 during the positive half cycle of the modulation signal, and B=0 during negative half cycle. CBSVM is based on comparison of modified sinusoidal reference signal ($V_k + V_{off} + V_{off}'$) with each carrier to determine the voltage level that the inverter should switch to. In this carrier based N level PWM operation consists of N-1 different carriers, where all carriers are in phase. A sequential switching signal and low frequency PWM signals are same for all full bridge converter cells. The base PWM signals (A, B, C and D) for hybrid PWM controller are shown in fig. 3.

Hybrid PWM controller is implemented using a simple combinational logic, and hence, it can be processed very quickly. The functions of the combinational logic for a five level hybrid PWM are expressed as

$$S1 = A\,B\,C + \overline{A}\,B \qquad S1' = A\,B\,D + \overline{A}\,B$$
$$S2 = \overline{A}\,B\,C + A\,\overline{B} \quad \text{and} \quad S2' = \overline{A}\,B\,D + A\,\overline{B}$$
$$S3 = \overline{A}\,\overline{B}\,C + A\,\overline{B} \qquad S3' = \overline{A}\,\overline{B}\,D + A\,\overline{B}$$
$$S4 = \overline{A}\,B\,C + A\,B \qquad S4' = \overline{A}\,B\,D + A\,B$$

In fig. 4, it is shown that each gate signal is composed of both low frequency PWM and CBSVM signals. If sequential switching signal A=1, S1, S2, S1' and S2' are operated with CBSVM while S3, S4, S3', and S4' are operated at fundamental frequency PWM. If sequential switching signal A=0, S1, S2, S1', and S2' are operated at fundamental frequency PWM while S3, S4, S3', and S4' are operated with CBSVM.
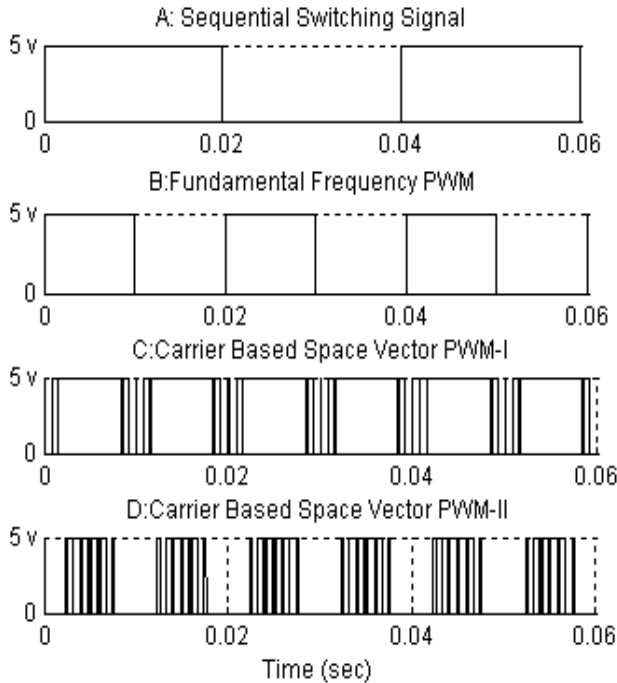
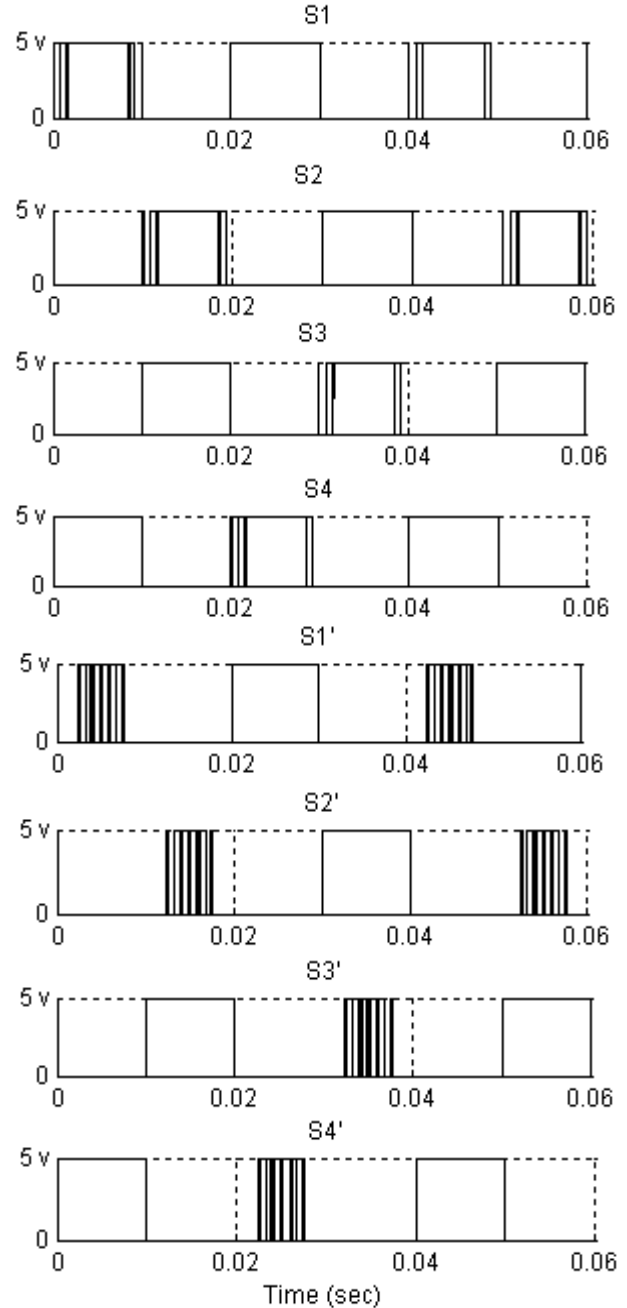Fig.3. Base PWM signals for five-level hybrid carrier-based space vector modulation (Phase a)

Fig.4. Hybrid carrier based space vector modulation signals for five phase five-level inverter (Phase a)

2.3 Generalized Hybrid PWM Algorithm Formulation

For completeness, the generalized formulation that suits for N level inverter and for any number of switching transitions is presented. The proposed algorithm for an N-Level Inverter is as follows:

(i) Obtain the number of inverter cells per phase K=N-1/2

(ii) Modify the peak amplitude of phase reference voltages V_a, V_b, V_c, V_d and V_e based on modulation index $M = A_m / K A_c$

(iii) Identify the instantaneous values of three phase reference voltages V_a, V_b, V_c, V_d and V_e and determine the values of V_{off} and V_{off}'.

(iv) Modified sinusoidal reference signal is obtained by $V_k' = V_k + V_{off} + V_{off}'$

(v) Comparison of modified sinusoidal modulating signal with each phase disposition carrier signal separately to generate K number of carrier based space vector modulation signals.

(vi) A common sequential signal and fundamental frequency PWM signals for each phase are obtained in synchronize with modulating signal

(vii) An independent hybrid PWM controller (combinational logic circuit) is used to mix low frequency PWM and the corresponding carrier based SVM (X) for each inverter cell.

$$Sx1 = A\ B\ X + \overline{A}\ B; \quad Sx2 = \overline{A}\ B\ X + \overline{A}\ \overline{B};$$

$$Sx3 = \overline{A}\ \overline{B}\ X + A\ \overline{B}; \quad Sx4 = \overline{A}\ B\ X + A\ B$$

(viii) Similarly, hybrid PWM pulses are developed for all cells in any level cascaded inverter. Totally 4K gate pulses per phase are developed to operate N level multilevel inverter.

3. Performance Analysis

3.1 Harmonic Analysis

The performance index namely weighted total harmonic distortion (WTHD) is chosen for the quantification of the proposed hybrid CBSVM. Weighted total harmonic distortion (WTHD) is superior to THD as a figure of merit for a non-sinusoidal inverter waveform in which lower portion of the frequency spectrum is weighted heavily, accurately portraying the expected harmonic current of an inductive load [8]. The WTHD uses spectral weighting factor and it is calculated using

$$WTHD = \frac{\sqrt{\sum_{n=2}^{50} \left(\frac{V_n}{n}\right)^2}}{V_1}$$ and plotted in fig.5. As

expected, the WTHD values are lower when the modulation index closer to unity and when the frequency ratio (mf) increases.

3.2 Power Loss Analysis

MATLAB-Simulink model of a five-phase five-level inverter has developed to study the power loss. The carrier frequency f_c is 2 kHz and each converter cell is connected to 200 v dc supply. The IGBTs selected are FF150R12KT3G, in which their maximum ratings are a forward current of 150 A and a direct voltage of 600 V. The semiconductor power losses can be estimated from the curves $(V_{sat}(\theta) \times I_1(\theta))$ and $(E(\theta) \times I_1(\theta))$, presented in the datasheet of each device, where : V_{sat} is the on-state saturation voltage ($V_{ce}(\theta)$ for the IGBT and $V_F(\theta)$ for the diode); $E(\theta)$ represent the energy losses in one commutation ($E_{on}(\theta)$ if it is a turn-on commutation, $E_{off}(\theta)$ if it is a turn-off commutation and $E_{rec}(\theta)$ if it is diode reverse recovery process). These curves are used in a MATLAB script developed to determinate the power losses. The mathematical models are found using points extracted from datasheets of each semiconductor device.

The mathematical models obtained for the IGBT module FF150R12KT3G are given by

$$V_{ce} = 1.15\, e^{0.0026\, I_1(\theta)} - 0.6654\, e^{-0.044\, I_1(\theta)}$$

$$V_F = 1.2\, e^{0.002\, I_1(\theta)} - 0.7258\, e^{-0.0475\, I_1(\theta)}$$

$$E_{rec} = 0.01806\, e^{-0.000412\, I_1(\theta)} - 0.0157\, e^{-0.00736\, I_1(\theta)}$$

$$E_{on} = 0.0051\, e^{0.0064\, I_1(\theta)} - 0.0037\, e^{-0.00811\, I_1(\theta)}$$

$$E_{off} = 0.0643\, e^{0.00121\, I_1(\theta)} - 0.0647\, e^{-0.00107\, I_1(\theta)}$$

$$I_1(\theta) = M * I_{max} \sin(\theta - \varphi)$$

where $I_1(\theta)$ is the load current, M is the modulation index, and φ is the load displacement angle. Based on the models for each device, the conduction and switching power losses are calculated for each semiconductor of the inverter.
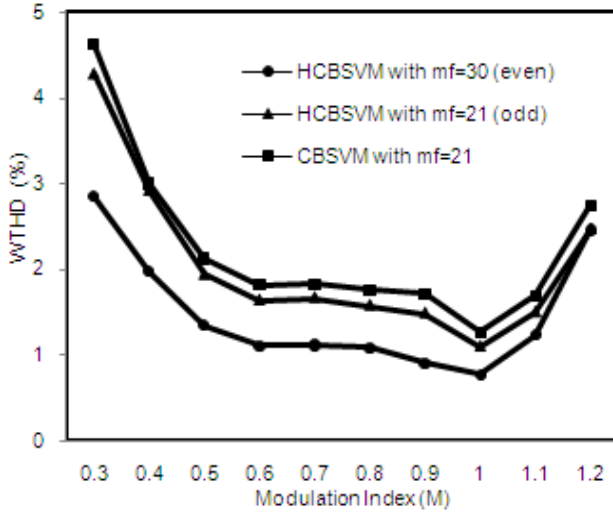
Fig.5. WTHD comparsion of hybrid CBSVM with conventional CBSVM for five level inverter

The total power loss is calculated based on the sum of switching loss and conduction losses. The switching loss for every power device (P_{sw}) is obtained separately using

$$P_{sw} = \frac{1}{T}\sum (E_{on} + E_{off} + E_{rec})$$ by

identifying every turn-on and turn-off instants during one reference period. Where E_{on} is turn on energy loss per commutation, E_{off} is turn off energy loss per commutation and E_{rec} is energy loss during reverse recovery process.
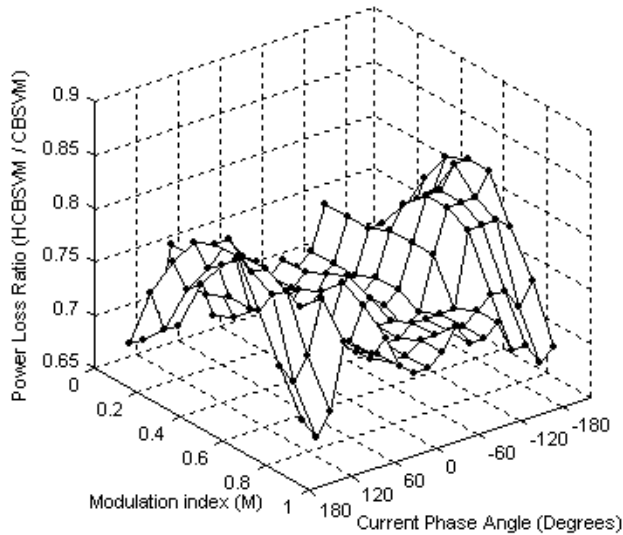

Fig.6 Ratio of the power losses of hybrid carrier based space vector modulation and conventional carrier based space vector modulation fed five-phase five-level inverter.

The conduction power losses are those that occur while the semiconductor device is conducting current. The calculation of conduction losses for each semiconductor of the inverter are given by

$$P_{cond\_IGBT} = \frac{1}{2\pi}\int_0^{2\pi} V_{ce}(\theta)*I_1(\theta)*V_{cmd}(\theta)\ d\theta$$

$$P_{cond\_D} = \frac{1}{2\pi}\int_0^{2\pi} V_F(\theta)*I_1(\theta)*V_{cmd}(\theta)\ d\theta$$

Where $V_{cmd}(\theta)$ is the PWM signal of the IGBT.

The sum of conduction losses for all IGBT's ($P_{cond\_IGBT\_T}$) and for all diodes ($P_{cond\_D\_T}$) is computed to obtain the total conduction losses.

$$P_{cond\_T} = P_{cond\_IGBT\_T} + P_{cond\_D\_T}$$

Fig.6 shows, for the full range of modulation index and the relative angle of the output currents, the ratio of total power losses (switching and conduction losses) for a five-phase five-level inverter with the proposed modulation strategy versus the conventional CBSVM technique. Note that the surface is always below one, which means that the power losses are significantly smaller for the proposed method. The mean value of the surface is found 0.7426 approximately; which means the power loss reduction is about 26%. The best case is produced for a unity power factor and modulation index is one.

4. Simulation and Experimental Results

In order to verify that the proposed PWM can be practically implemented in a five phase multilevel inverter, simulations were performed by using MATLAB/Simulink software. It also helps to confirm the PWM switching strategy which can be implemented in a digital signal processor (DSP) and complex programmable logic device (CPLD). The load resistance and inductance are 10Ω and 15mH, and the dc bus voltage is set at 100 V. The inverter is operated in linear modulation range and the corresponding phase voltage waveforms with FFT analysis as shown in fig.7 (a)-(b). It can be seen that all the lower order harmonics are absent and the fundamental is controlled at the pre-defined value. It is interesting to note that the next significant harmonic will be 37th for frequency ratio of 21. The significant harmonics are 37, 39, 41, and 45, which are high frequency, with the RMS values under 12% of the fundamental term. In addition, the current waveform appears highly sinusoidal due to inherent low voltage distortion provided by multilevel PWM

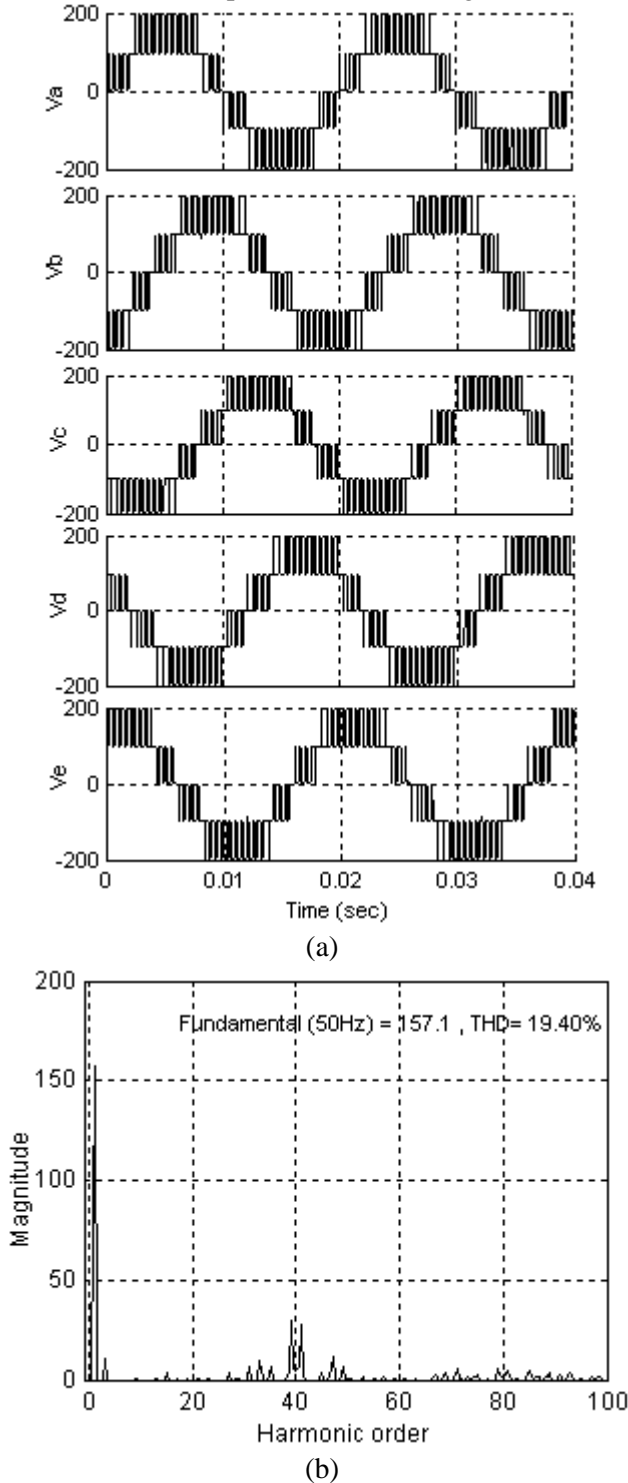operation. This can be clearly appreciated with current harmonic spectrum shown in fig.8 (b).

(a)

(b)

Fig.7. Simulation results for five phase five-level inverter with hybrid CBSVM for f_o = 50 Hz, f_c =1050 Hz ,and modulation index M=0.8 (a) Output phase voltage waveforms. (b) Phase voltage spectrum (Va).
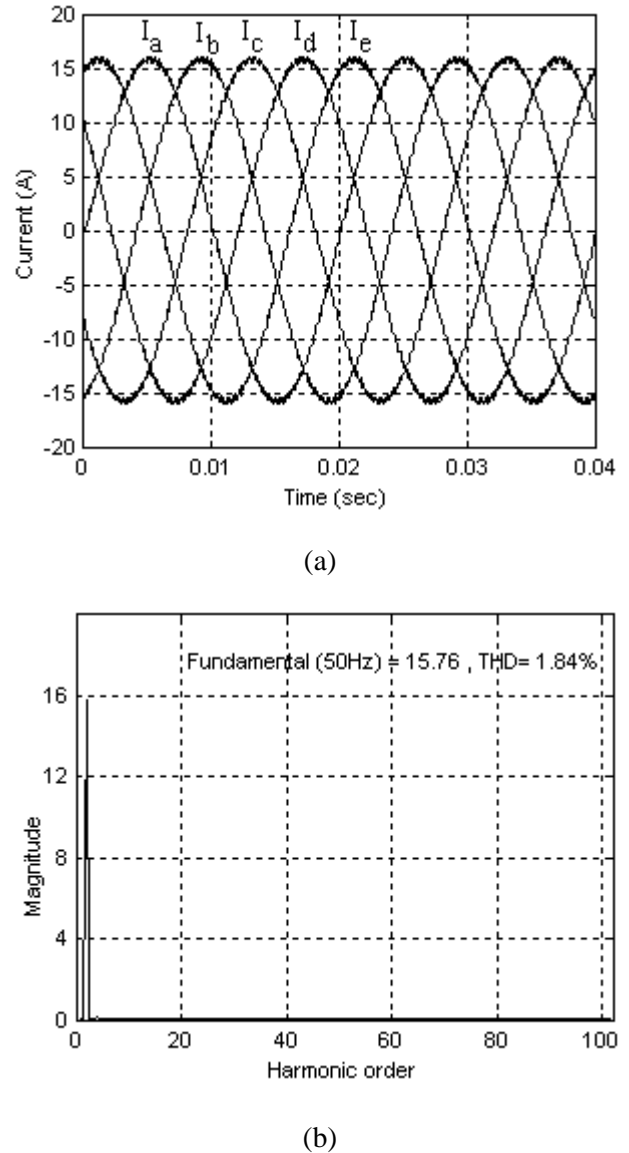

(a)

(b)

Fig.8. Simulation results for five phase five-level inverter with hybrid CBSVM for f_o = 50 Hz, f_c =1050 Hz ,and modulation index M=0.8 (a) Phase current waveforms. (b) Phase current spectrum.

To verify the validity of the proposed hybrid modulation, a five phase five-level inverter is designed to implement this scheme. Fig.9 shows the functional block diagram of the laboratory based prototype of a five level inverter (one phase leg) that is implemented with eight insulated gate bipolar transistor (IGBT) switches with internal anti-parallel diodes. The base PWM pulses (fundamental frequency PWM and CBSVM) are generated using low cost high speed Texas instruments TMS320F2407 digital signal processor (DSP) board with an accuracy of $20\,\mu s$.
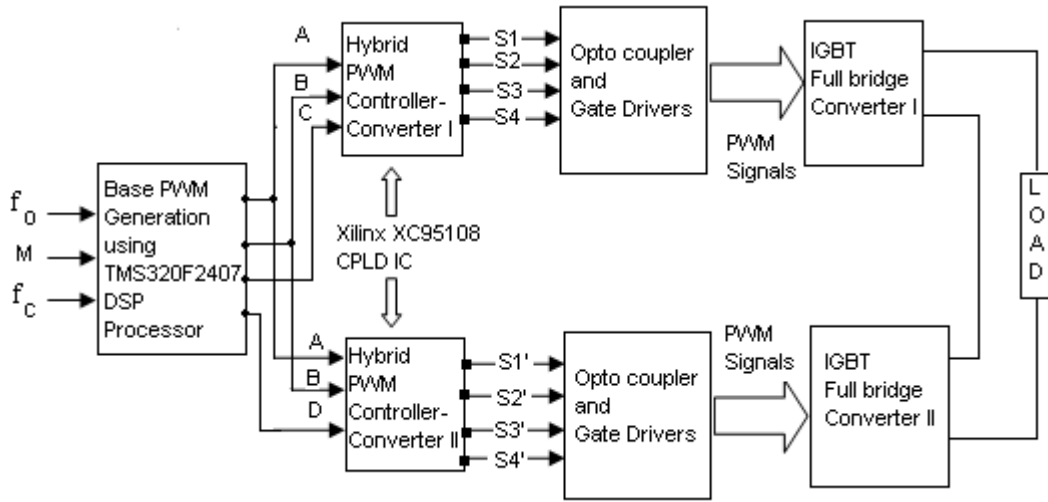
Fig.9.Functional block diagram of hybrid CBSVM implementation (one phase)

A sequential signal also generated to operate each IGBT with fundamental frequency PWM and CBSVM sequentially to equalize power losses, heating among the devices. Hybrid PWM control algorithm based on combinational logic is developed and it is implemented in Xilinx CPLD XC95108 IC. CPLD controller combines fundamental frequency PWM, sequential signal and CBSVM to generate hybrid CBSVM pulses for a five level cascaded inverter. XC95108 IC is used to develop the control algorithm which suited for this application that has the features of better response for high frequency input signals, narrow pulse width pulses and no jitter of the delay in the circuit. The optically coupled isolators MCT2E are used to provide an electrical isolation between the Xilinx CPLD controller board and the power circuit. Four high voltage high speed IGBT drivers (IR2112) are used to provide proper and conditioned gate signals to the power switches. A digital real time oscilloscope (Tektronix TPS2024) is used to display and capture the output waveforms and with the feature of the fast Fourier transform (FFT), the spectrum of the output voltage is obtained for different operating points as discussed hereafter.

The dc bus voltage is set at 100 V and the frequency of modulated wave and carrier wave are 50 Hz and 1050 Hz respectively. Selected experimental results for five phase five-level inverter are obtained and validated the simulation results. Specifically, Fig.10 (a) shows the phase voltage and current waveform of the proposed five-level HCBSVM for standard modulation range and the associated spectrum is presented in fig.10 (b) and (c). It is confirmed that the harmonic cancellation up to sidebands around $2f_c$ (2100 Hz) is achieved in the voltage waveform and the first significant harmonic is the 39th as predicted.
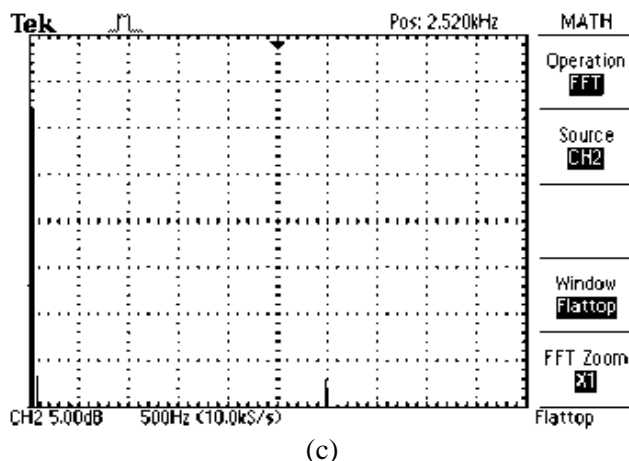

(a)

(b)

(c)
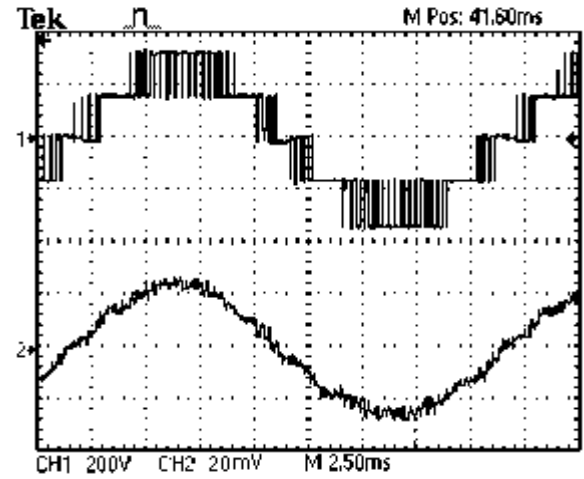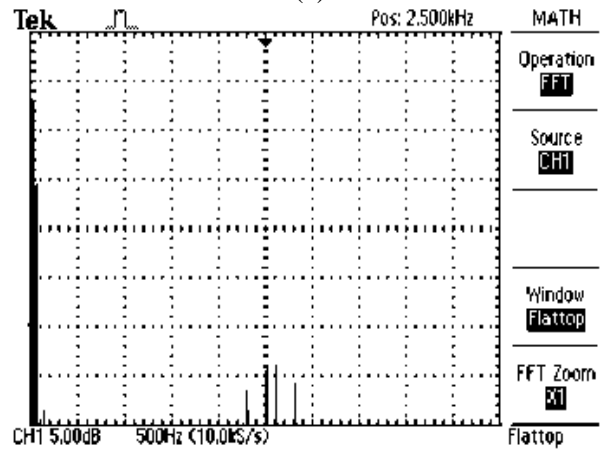
Fig. 10. Experimental results of the five phase five-level inverter with hybrid CBSVM for $f_o = 50$ Hz, $f_c = 1050$ Hz , and modulation index M=0.8. (a) Phase voltage and current waveform. (b) Phase voltage spectrum. (c) Phase current spectrum

5. Conclusion

In this paper, a hybrid carrier based space vector modulation technique for multiphase multilevel inverter has presented. The hybrid PWM control algorithm is based on combination of fundamental frequency PWM and carrier based space vector modulation for multiphase inverter operation. Compared to conventional CBSVM, the reduced numbers of switching (up to 33%) are obtained while achieving the same fundamental voltage tracking and it offers 26% of power loss saving. The best case is produced at unity power factor and unity modulation index in which power loss saving is about 29%. It is shown that the better harmonic performance of proposed PWM strategy compared to its CBSVM in the entire range of modulation index. It is valid for any number of phases or levels and it can be used with standard cascaded multilevel inverter topologies. In addition, the proposed algorithm is suitable for real time implementation due to its low computational complexity. Selected simulation and experimental results are reported to confirm the validity of the proposed technique.

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