# Performance Improvement of Multiphase Multilevel Inverter Using Hybrid Carrier Based Space Vector Modulation

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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 inherits the features of fundamental frequency modulation and carrier based space vector modulation strategies. The main characteristics of this hybrid modulation are the reduction in power 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. Theoretical considerations are detailed using a five phase multilevel inverter. 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. Simulation and experiment results confirm the good performance of the proposed modulation scheme.
**Keywords:** Digital signal processor, hybrid carrier based space vector modulation, multiphase multilevel inverter, harmonic analysis, power loss analysis.

## 1. Introduction

Recent developments in the area of multiphase variable speed drives, initiated predominantly by potential applications in electric ship propulsion, more-electric aircraft, locomotive traction, electric and hybrid-electric vehicles, and other high power industries, have led to a corresponding development of pulse width modulation (PWM) schemes for multiphase inverters used in these drives [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 Figure1 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. By and large, the emphasis has been placed on space vector PWM (SVPWM) methods. SVPWM offers great flexibility to optimize switching waveforms and is suited for digital implementation. However, due to constant sampling rate used in SVPWM, the equivalent carrier-based techniques have been developed. Carrier-based

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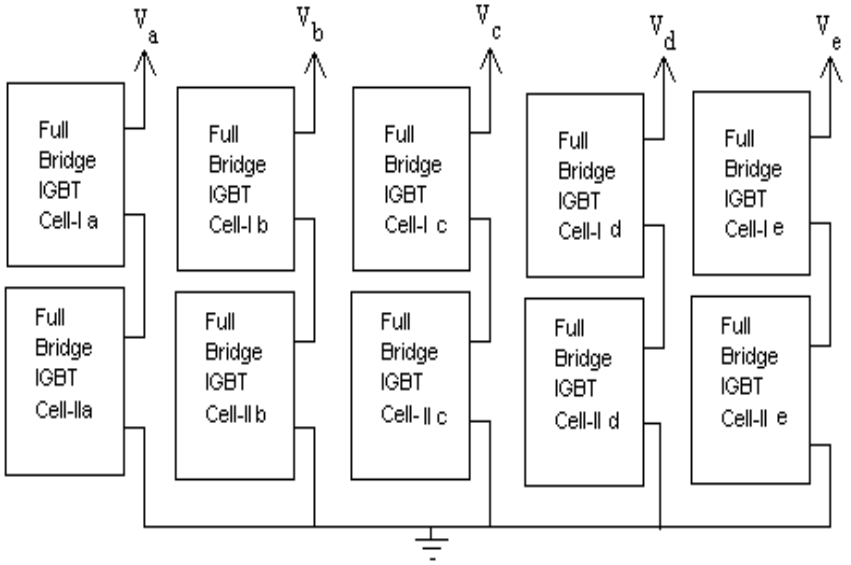
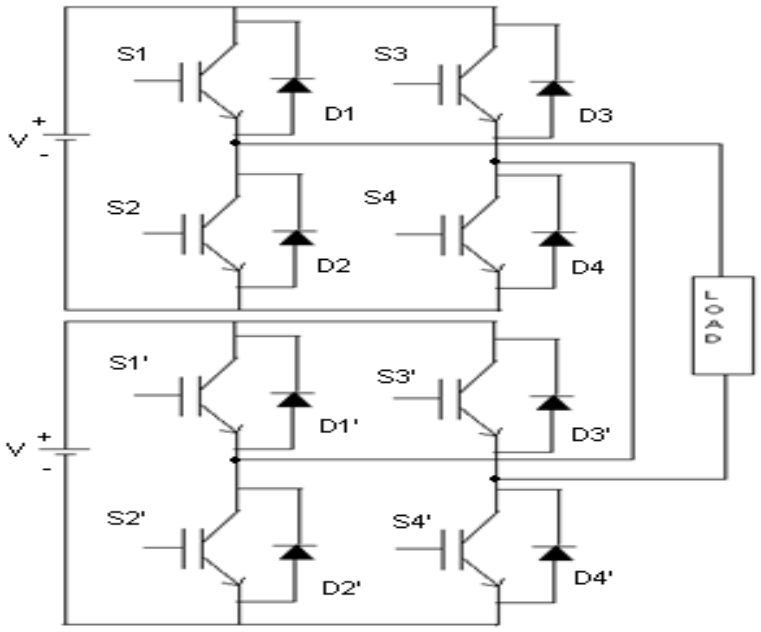
space vector modulation (CBSVM) is appropriate for inverters with more than five levels, where the computational overhead for conventional SVPWM is exceeding due to many output states [6].




(a)




(b)

Figure 1. (a) Schematic diagram of the five phase multilevel inverter topology.
(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. High Efficiency Hybrid Modulation Development

*A. 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:

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

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

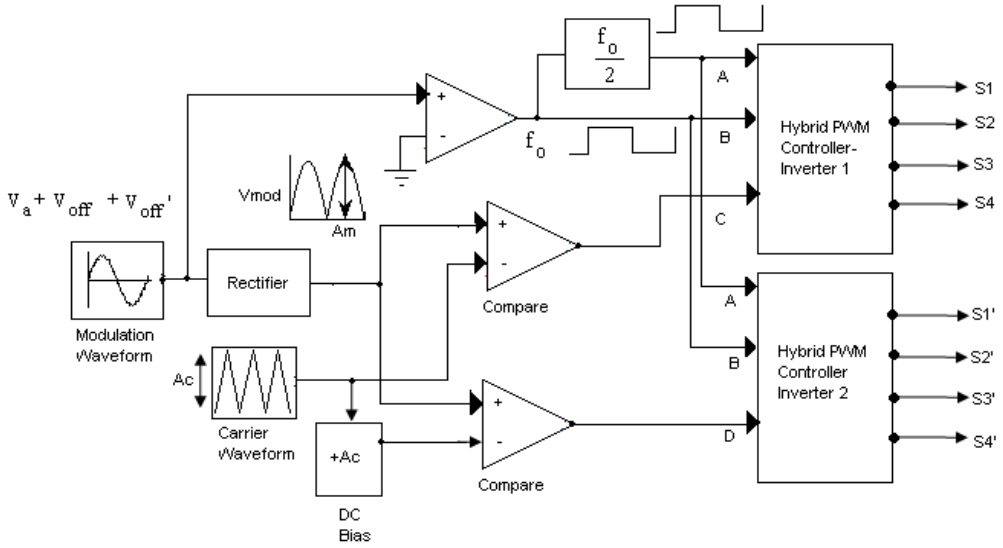
$$V_{off}{}' = \frac{V_{dc}}{N-1} - \frac{\max(V_a', V_b', V_c', V_d', V_e') + \min(V_a', V_b', V_c', V_d', V_e')}{2} \tag{3}$$

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.

*B. 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 Figure 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 Figure 3.




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

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

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

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

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

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

$$\begin{aligned} S1 &= A\,B\,C + \overline{A}\,B & S1' &= A\,B\,D + \overline{A}\,B \\ S2 &= A\,B\,C + \overline{A}\,\overline{B} & S2' &= \overline{A}\,B\,D + \overline{A}\,\overline{B} \\ S3 &= \overline{A}\,\overline{B}\,C + \overline{A}\,\overline{B} & S3' &= \overline{A}\,\overline{B}\,D + A\,\overline{B} \\ S4 &= \overline{A}\,B\,C + A\,B & S4' &= \overline{A}\,\overline{B}\,D + A\,B \end{aligned} \quad \text{and} \quad (4)$$

In Figure 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.

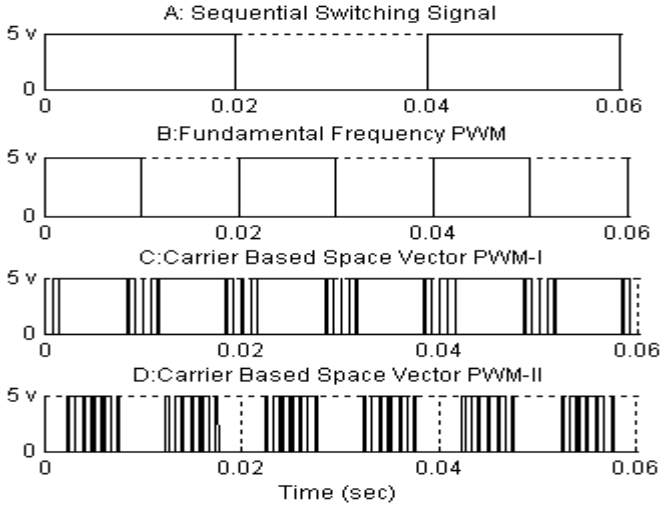



Figure 3. Base PWM signals for five-level hybrid carrier-based space vector modulation (Phase a)

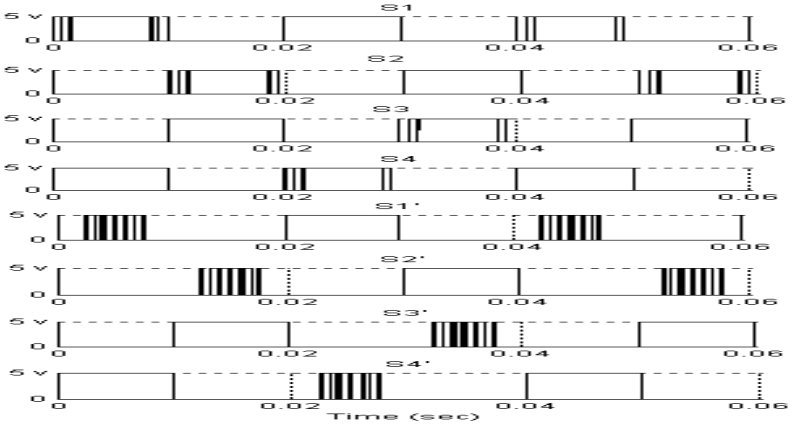



Figure 4. Hybrid carrier based space vector modulation signals for five phase five-level inverter (Phase a)

## 3. Performance Analysis

*A. 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 (5) and plotted in Figure5. As expected, the WTHD values are lower when the modulation index closer to unity and when the frequency ratio (mf) increases.

$$\text{WTHD} = \frac{\sqrt{\sum_{n=2}^{50} \left(\frac{V_n}{n}\right)^2}}{V_1} \tag{5}$$

The proposed hybrid PWM scheme is also implemented in seven, nine, eleven level cascaded inverter and the harmonic performances are provided. The total harmonic distortion of a signal is the ratio of the sum of the powers of all harmonic frequencies above the fundamental frequency to the power of the fundamental frequency. The THD is calculated using (6) up to 50$^{th}$ order of harmonics and is plotted in Figure6. It is obviously found that the proposed hybrid PWM offers lower THD compared to conventional PWM one, thus the superiority.

$$THD = \frac{\sqrt{\sum_{n=2}^{50} V_n^2}}{V_1} \tag{6}$$

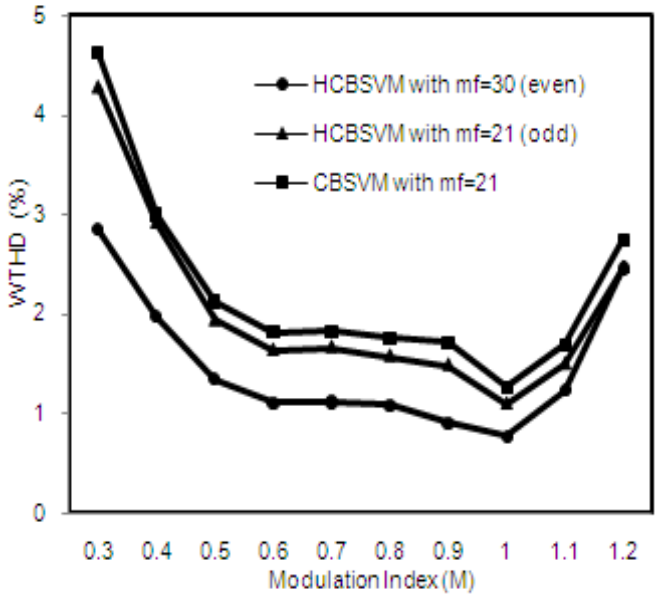



Figure 5. WTHD comparsion of hybrid CBSVM with conventional CBSVM for five level inverter

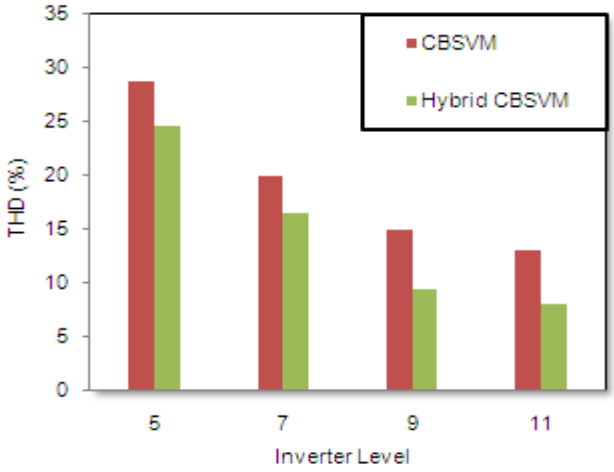



Figure 6. THD comparision for multiphase multilevel inverter at modulation index $M$=0.9 and carrier frequency $f_c$=1500 hz

*B. Power Loss Analysis*

Power losses in multilevel converters can be classified in to four types, as follows: Conduction losses; switching losses; Snubber losses; OFF-state losses. The last category is usually omitted, as these losses are insignificant. Snubber losses can be important in some kinds of power devices, such as gate turnoff thyristors. However, snubbers are not usually required in converters made by other devices, such as insulated-gate bipolar transistors (IGBTs) [9].Thus, only conduction and switching losses will be considered in this paper. New high-power devices can switch faster. Since switching losses are directly related to the switching frequency, these losses are usually greatest in PWM power converters.

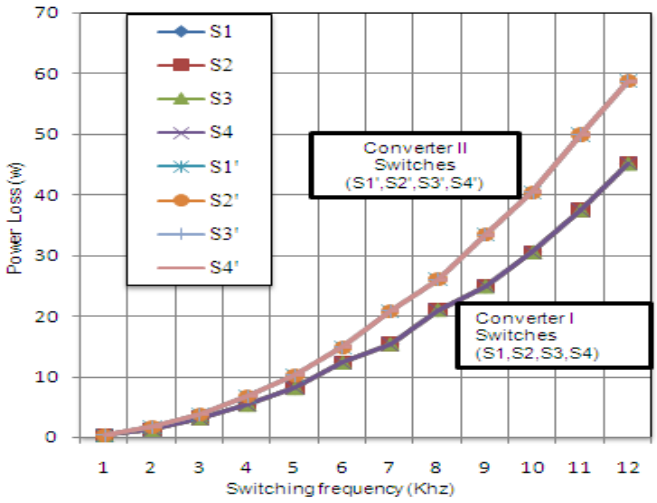
MATLAB-Simulink model of a five-phase five-level inverter has developed to study the power loss. The carrier frequency $f_c$ is 2 kHz and each converter cell is connected to 200 v dc supply. The IGBTs selected are IRG4BC20SD, in which their maximum ratings are a forward current of 19 A and a direct voltage of 600 V. Switching losses are generated during the turn-on and turnoff switching processes of the power devices. In such processes, the voltages and currents can take significant values simultaneously. Therefore, their instantaneous power can reach high values. Fortunately, these processes only last for short periods, although they are repeated several times within a second. For this reason, they are directly related to the switching frequency. The average switching losses are calculated based on the information from the data sheet, turn on energy losses per pulse ($E_{on}$), turn off energy losses per pulse ($E_{off}$) including reverse recovery loss and switching frequency $f_c = 1/T_c$ .

$$P_{sw} = \frac{1}{2\pi T_c} \sum (E_{on} + E_{off} + E_{rec}) \tag{7}$$

The conduction power losses are those that occur while the semiconductor device is conducting current. The conduction losses of the transistors are obtained from the linearization of the static characteristics of the power switches. The model of the switches in the ON-state is represented by a voltage source and a series resistor. Consequently, the mean value of the conduction losses in a power device can be approximated by the following:

$$P_{cl} = \frac{1}{2\pi} \int_{0}^{2\pi} (V_{Fo} + i_F R_{on}) i_F \, dt \tag{8}$$

in which $V_{fo}$ is the threshold voltage, $R_{on}$ is the dynamic resistance of the model and $i_f$ is the forward current in the device. The values were obtained by drawing a straight line tangent to the characteristic curves of the device, taking into account the current magnitude in this application. The total power loss is calculated based on the sum of switching loss and conduction losses. This proposed reduces the power loss up to 28 % and equalizes the power losses among the power switches in each inverter cell. In practical high power systems, saving power losses becomes important to improve the efficiency of the system.

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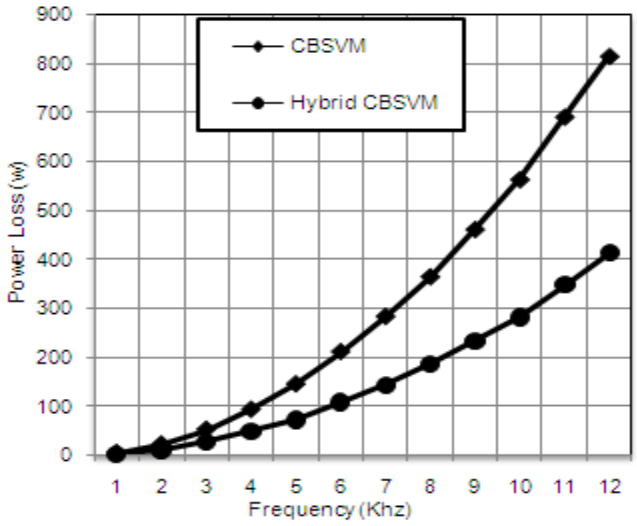
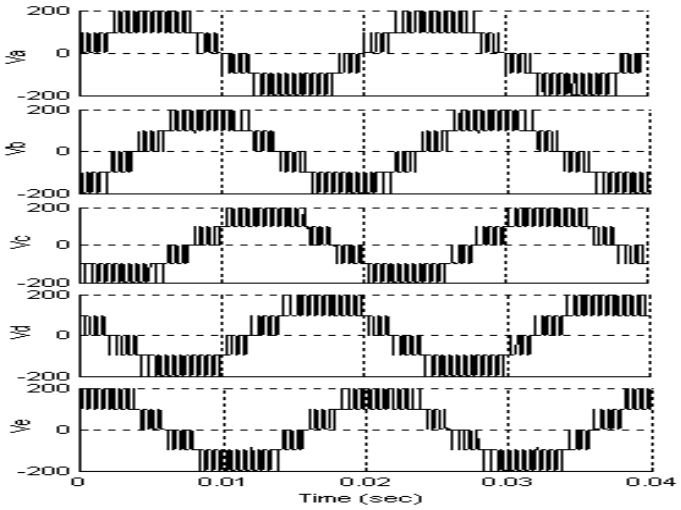



(b)

Figure 7. (a) Power loss comparison of the proposed modulation with standard five-phase multilevel inverter. (b) Power loss distribution among the power devices for one phase leg.

**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 Figure8 (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 $37^{th}$ for frequency ratio of 40. 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 Figure9 (b).

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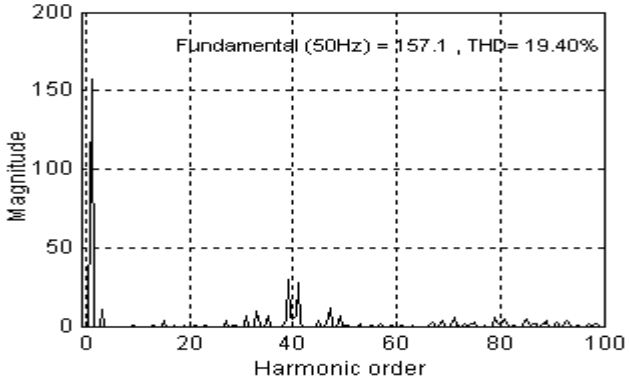
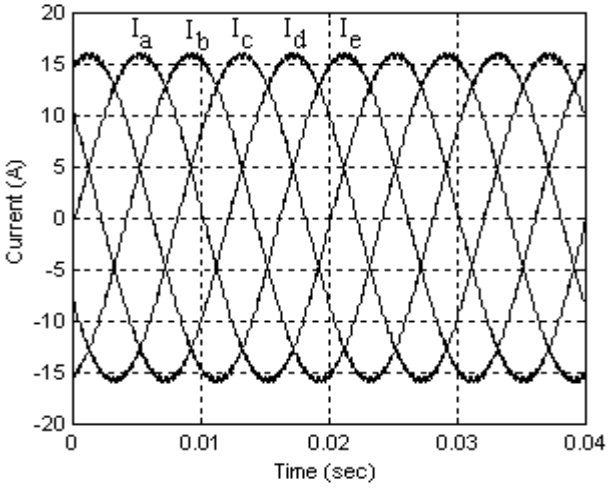



(b)

Figure 8. Simulation results for five phase five-level inverter with hybrid CBSVM for $f_o$ = 50 Hz, $f_c$ =2kHz ,and modulation index M=0.8 (a) Output phase voltage waveforms.

(b) Phase voltage spectrum ($V_a$).

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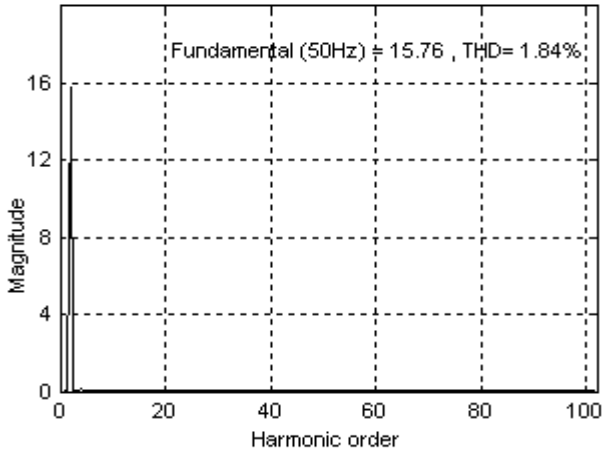
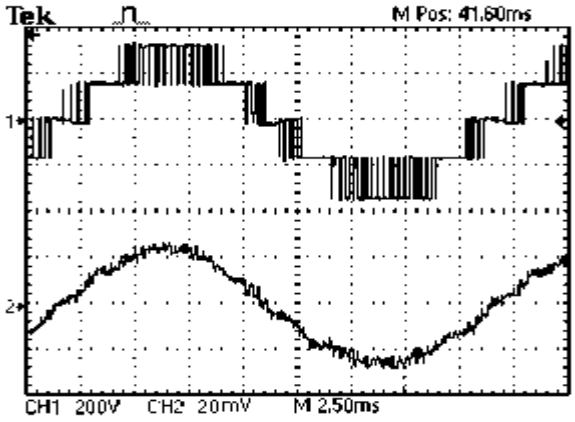



(b)

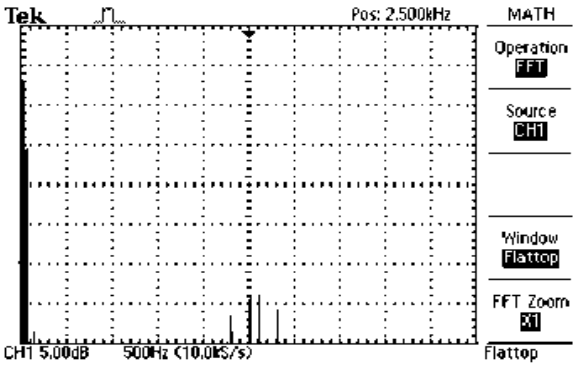
Figure 9. Simulation results for five phase five-level inverter with hybrid CBSVM for $f_o$ = 50 Hz, $f_c$ =2 kHz ,and modulation index M=0.8 (a) Phase current waveforms. (b) Phase current spectrum.

The practicality and performance of the proposed hybrid modulation has been verified experimentally using a five phase five-level inverter. It is implemented with eight insulated gate bipolar transistor (IGBT) switches with internal anti-parallel diodes for each phase. 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 μs . 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. 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. The DC bus voltage is set at 200 V and the frequency of modulated wave




(a)

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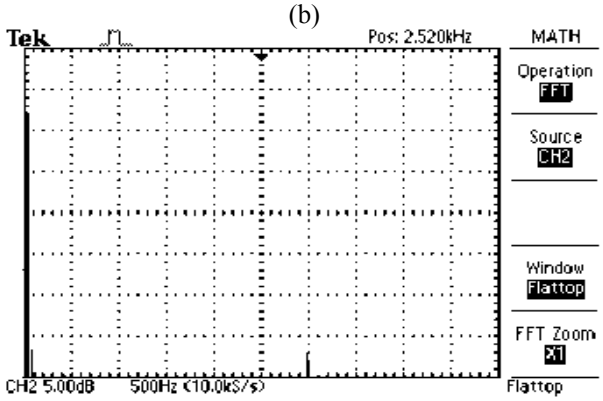


(c)

Figure 10. Experimental results of the five phase five-level inverter with hybrid CBSVM for $f_o$ = 50 Hz, $f_c$ =2000 Hz , and modulation index M=0.8. (a) Phase voltage and current waveform. (b) Phase voltage spectrum. (c) Phase current spectrum

and carrier wave are 50 Hz and 2000 Hz respectively. Selected experimental results for five phase five-level inverter are obtained and validated the simulation results. Specifically, Figure10 (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 Figure10 (b) and (c). It is confirmed that the harmonic cancellation up to sidebands around $f_c$ (2000 Hz) is achieved in the voltage waveform and the first significant harmonic is the $39^{th}$ as predicted. As seen from the FFT analysis, all the harmonics up to $40^{th}$ order have been minimized, and the output voltage results in very low THD. Experimental results also validate the computational and simulation results.

## 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. The proposed modulation offers 28% of power loss saving and makes better performance at unity power factor and unity modulation index (M=1) in which power loss saving is about 31%.The improvement of the efficiency is a consequence of the hybrid modulation and not due to over dimensioning of the power circuit. 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.

## References

[1] E. Levi, R. Bojoi, F. Profumo, H. A. Toliyat, and S. Williamson, "Multiphase Induction Motor Drives-A Technology Status Review," *IET Elect. Power* Appl., vol. 1, no. 4, pp. 489–516, Jul. 2007.

[2] L. M. Tolbert, F. Z. Peng, and T. G. Habetler, "Multilevel Converters For Large Electric Drives," *IEEE Trans. Ind. Appl*., vol. 35, no. 1, pp. 36–44, Jan. 1999.

[3] J. Rodríguez, J. S. Lai, and F. Z. Peng, "Multilevel Inverters: A Survey Of Topologies, Controls And Applications," *IEEE Trans. Ind. Electron*., vol. 49, no. 4, pp. 724–738, Aug. 2002.

[4] A. Iqbal and E. Levi, "Space Vector PWM Techniques For Sinusoidal Output Voltage Generation With A Five-Phase Voltage Source Inverter," *Electr. Power Compon. Syst*., vol. 34, no. 2, pp. 119–140, Feb. 2006.

[5] Drazen Dujic, Gabriele Grandi, Martin Jones, and Emil Levi, "A Space Vector PWM Scheme For Multi Frequency Output Voltage Generation With Multiphase Voltage-Source Inverters", *IEEE Trans. Ind. Electron*., vol. 55, no. 5, May 2008.

[6] 6. Óscar López, Jacobo Álvarez, Jesús Doval-Gandoy, and Francisco D. Freijedo, "Multilevel Multiphase Space Vector PWM Algorithm", *IEEE Trans. Ind. Electron*., vol. 55, no. 5, may 2008

[7] Atif Iqbal, and Shaikh Moinuddin, "Comprehensive Relationship Between Carrier-Based PWM and Space Vector PWM in a Five-Phase VSI", *IEEE Trans. power. Electron*, vol. 24, no. 10, oct 2009

[8] T. J. Kim, D. W. Kang, Y. H. Lee, D. S. Hyun, "The analysis of conduction and switching losses in multilevel inverter system", *in proc. of the 32th Power Electronics Specialists Conference and Applications*, pp.1363-1368, 2001.

[9] D. G. Holmes and T. A. Lipo, Pulse Width Modulation for Power Converters: Principles and Practice, *IEEE Press, Piscataway*, NJ, 2003.

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