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

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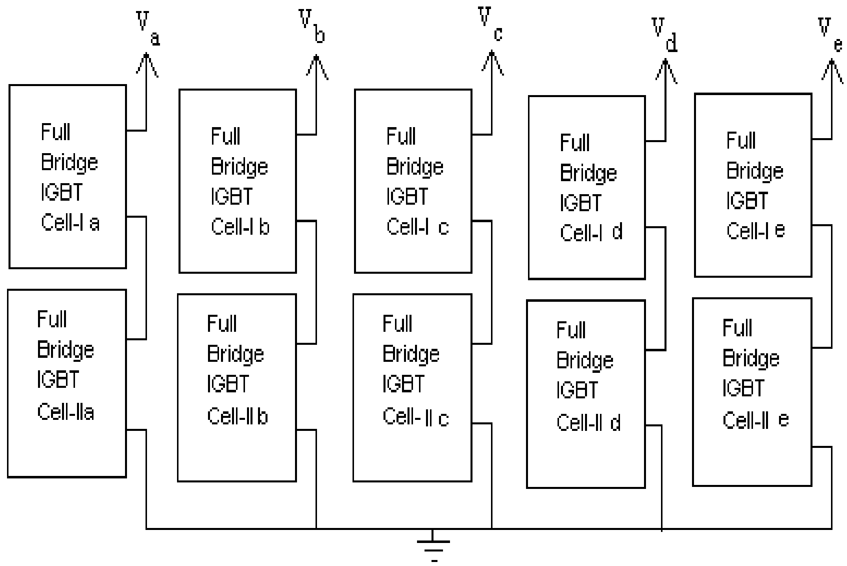
Abstract: This paper proposes a hybrid carrier based space vector modulation suitable for multiphase multilevel inverters. Multiphase multilevel inverters are controlled by this hybrid modulation to provide multiphase variable voltage and variable frequency supply. The proposed modulation inherits the 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.

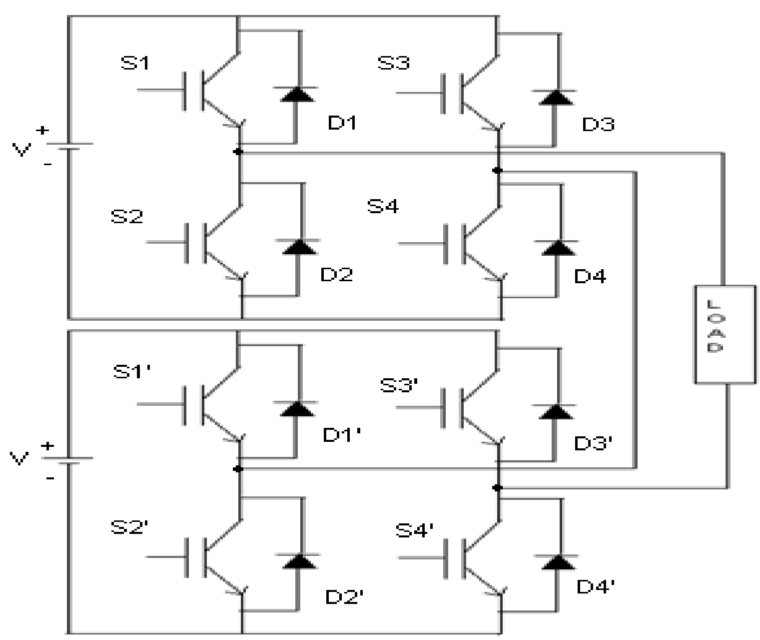
1. Introduction

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 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)



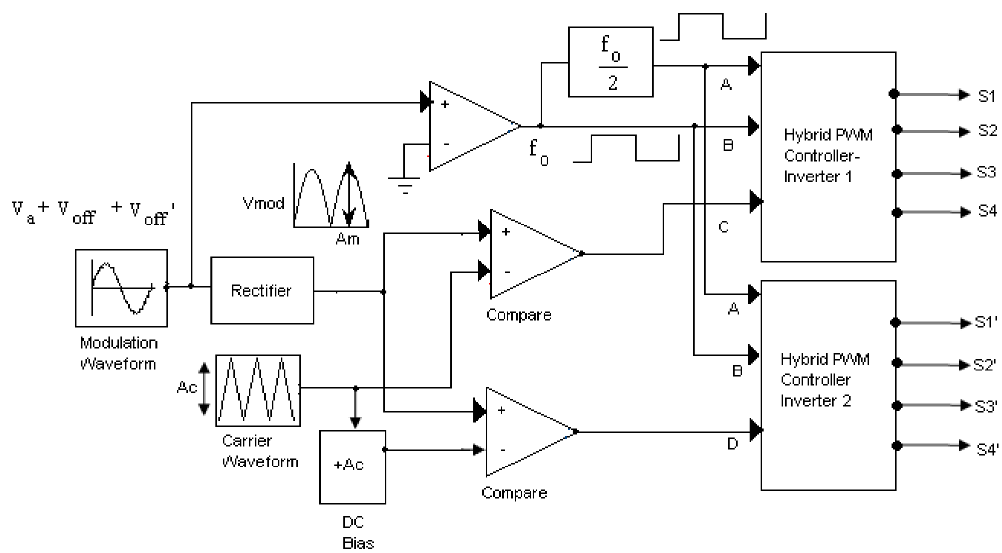
(b)

Figure 1. (a) Schematic diagram of the five phase multilevel inverter topology.
(b) Power circuit configuration for one phase leg.

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)

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.

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

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.

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

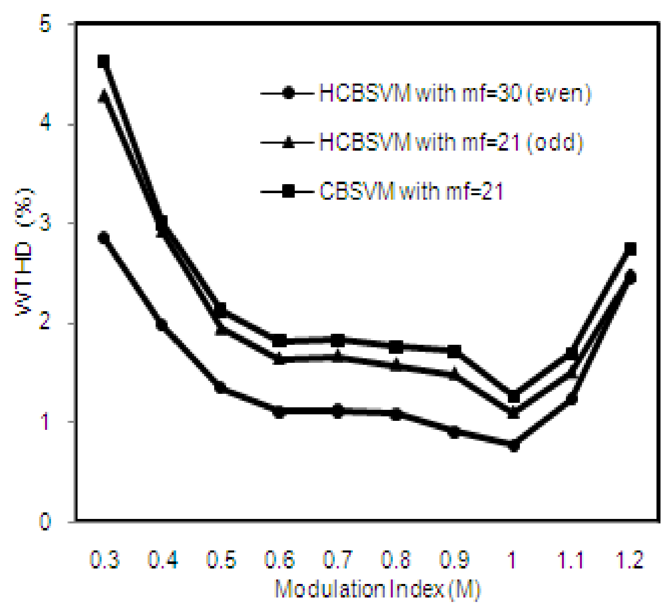
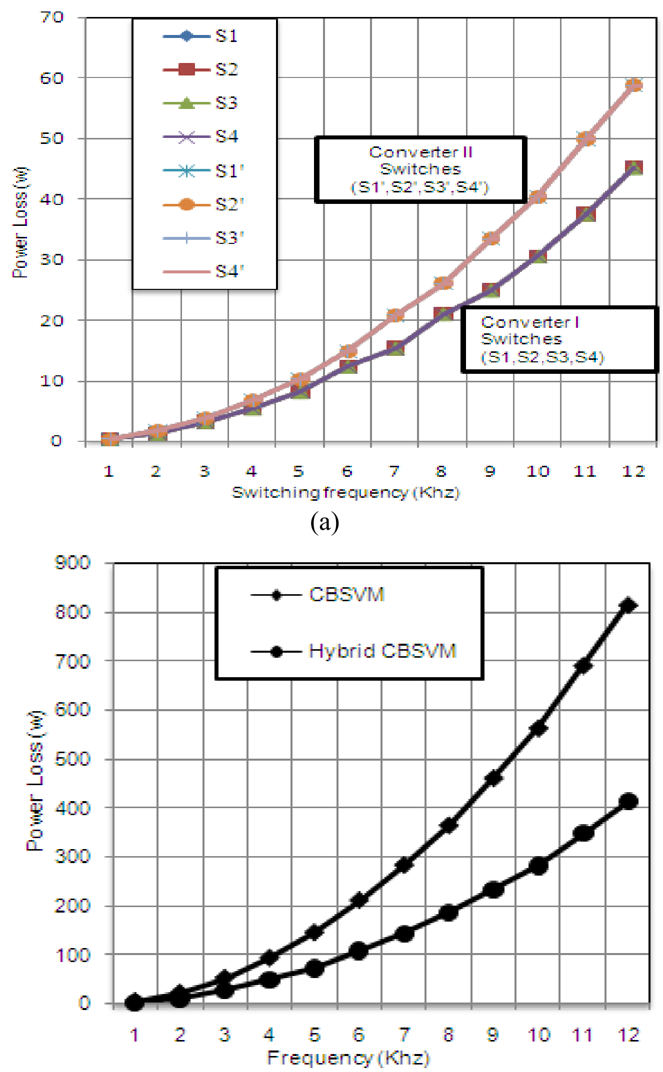


Figure 5. WTHD comparsion of hybrid CBSVM with conventional CBSVM for five level inverter

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

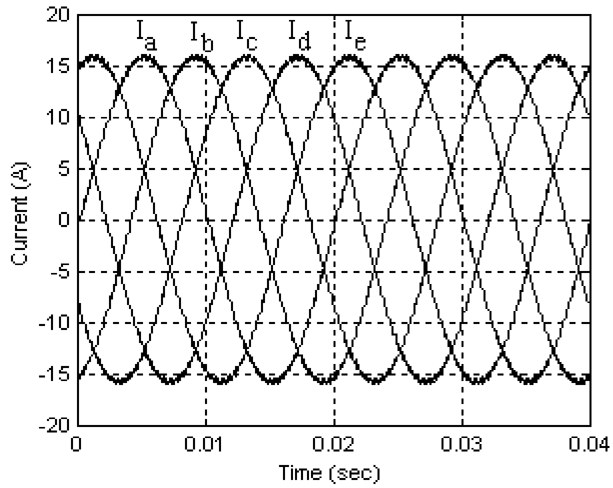
in which V_{fo} is the threshold voltage, R_{on} is the dynamic resistance of the model and i_f is the forward current in the device. The values were obtained by drawing a straight line tangent to the characteristic curves of the device, taking into account the current magnitude in this application. 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.



(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.

(b) Phase voltage spectrum (V_a).



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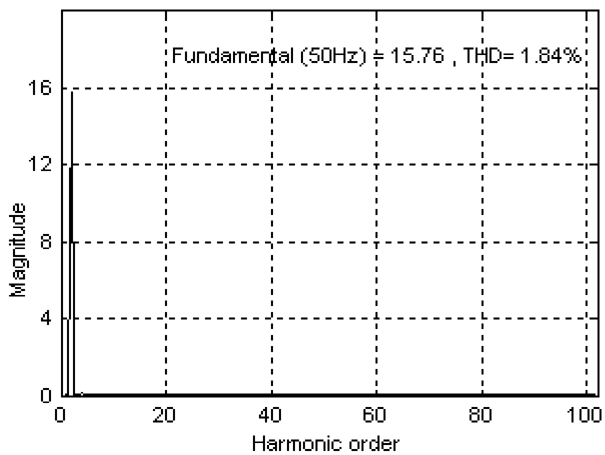

(b)

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

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 39th as predicted. As seen from the FFT analysis, all the harmonics up to 40th 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.

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