A Novel Modified Carrier PWM Switching Strategy for Single-Phase Full-Bridge Inverter

S. Jeevananthan, P. Dananjayan, and S. Venkatesan

***Abstract*—A novel pulse width modulation (PWM) switching strategy is developed through carrier modification, which eliminates the restriction in the fundamental component of a conventional switching scheme in the linear region. The proposed strategy is suitable for single-phase full-bridge inverter. The performance evaluation and comparison are based on the fundamental component, the total harmonic distortion (THD) and number of pulses per cycle. The aim of the novel method is to achieve overmodulated fundamental voltage values with modulation depths in the linear range, while improving THD and further reducing lower order harmonics dominancy. A significant enhancement in performance is validated by simulation and numerical commutations. In addition, a performance comparison of proposed method with harmonic injection PWM methods is also provided.**

***Index Terms*—Inverter, total harmonics distortion (THD), fundamental enhancement, modified carrier pulse width modulation (MCPWM), overmodulation.**

I. INTRODUCTION

THE OBJECTIVE of pulse width modulation (PWM) technique in dc-ac converter environment is to shape the output voltage spectra in a way beneficial to the application. Spectra shaping serves to eliminate lower order harmonics and keeps the dead band as wide as possible for a given switching frequency. Various control strategies are available for controlling the fundamental component and total harmonics distortion (THD). They have different implementations, dynamics responses, PWM patterns and harmonics content [1], [2].

Though sinusoidal pulse width modulation (SPWM) renders many advantages viz. spectral occupancy, ease of filtering, linearity in fundamental control, etc., it has few disadvantages. The foremost one is fundamental magnitude restriction. It can be overcome through overmodulation by increasing duty cycle (merging of pulses at centre) [3]. However, operating beyond the modulator voltage linearity limit introduces lower order harmonics. Another obvious requirement in most PWM switching environments is minimization of unwanted harmonics, i.e., a THD. A number of PWM strategies have been developed to reduce THD, eliminate selected harmonics, minimize filtering requirement, minimize harmonic losses, reduce switching losses, and be suitable for on line (computational free) implementation.

Several attempts have been made in the last few decades to develop PWM schemes, which are different in concept and performance [4]-[8]. In 1999, Chen and Cheng have proposed an analog-based modified PWM control scheme to eliminate low order harmonic components caused by the non-constant dc voltage [9]. Mazzucchelli and Puglesi have carried out an extension of the “subharmonic” method in 1981 [10]. This method has enabled to obtain the inverter output waveform variable continuously from a nearly sinusoidal to square wave and aimed at increasing the amplitude of the output fundamental without further adverse effects. Inverter harmonic reduction using Walsh function harmonic elimination method has been presented in [11]. The developed algorithm finds optimized switching angles by solving linear algebraic equations instead of solving non-linear transcendental equations. The optimized, minimal THD pattern has been recently reported [12], [13] and paper [14] has presented a method to eliminate the selected harmonics. For medium and high power inverter applications, since the maximum switching frequency is restricted by the turn-off time, conduction, and switching losses of the switching devices, a PWM technique with lower switching frequency is preferred.

The purpose of this paper is to propose a modified SPWM control scheme, which offers an improved performance in comparison to the existing switching strategies in terms of harmonic distortion, THD and fundamental component, especially at low switching frequency. The modified carrier PWM technique (MCPWM) is developed to give an improved fundamental inverter output waveform without involving significant changes in device (conduction and switching) losses.

II. PWM SWITCHING STRATEGY FOR SINGLE-PHASE FULL-BRIDGE INVERTER

A switching sequence for the basic single-phase full-bridge inverter, shown in Fig. 1, which consists of two switching poles, S_1/S_2 and S_3/S_4, there are 2^4=16 different possible combinations of switching. Only four of these combinations are useful for obtaining the PWM pattern across the inverter output as shown in Table I.

PWM schemes presented in this study are assumed to be synchronous PWM. A unidirectional triangular carrier and rectified pulsating sinusoidal reference are considered as shown in Fig. 2 for analysis in this paper.

In the SPWM switching strategies, fundamental improvement (particularly when dc link voltage is of finite value) demands an increase in width of pulses in the regions around the center of the reference, i.e., a reduction in number of commutation by pulse dropping [3]. The reference output voltage relationship is linear until the reference voltage magnitude exceeds the modulator

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Manuscript received December 14, 2004, revised July 23, 2005.

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Publisher Item Identifier S 1682-0053(05)0333

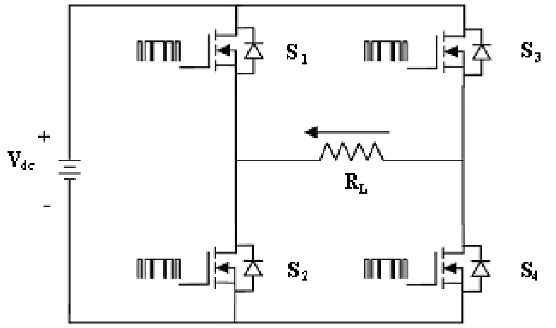


Fig. 1. Single-phase full-bridge inverter.

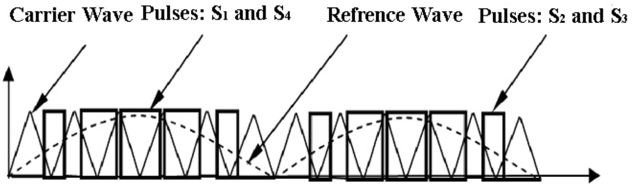


Fig. 2. Gating pulse generation considered.

TABLE I
SWITCHING COMBINATIONS

Conducting switches	Output voltage
S_1, S_4	$+V_{dc}$
S_3, S_2	$-V_{dc}$
S_1, S_2	0
S_3, S_4	0

linearity limit and the condition is called overmodulation. When the dc link voltage of a PWM utility has a finite value, the voltage linearity of a modulator is confined to a limited voltage range, as the higher voltage values are to be obtained by increasing the inverter gain. The system looses the linearity over the fundamental and introduces many more harmonics in the side bands as compared to the linear range.

III. NOVEL TECHNIQUE

A. Carrier Modification

The basic principle of the proposed switching strategy is a modification of triangular carrier, grouping two adjacent triangles of carrier wave around the mid-region of the sinusoidal reference and incorporating phase shift keying for 180-degree, which increases the width of the pulses occurring in that region of the sinusoidal reference signal. This is basically a pre-modulation process on the carrier wave to invert the carrier sections, and thereby introduces a controlled degree of non-linear sampling to maximize PWM fundamental voltage while minimizing THD.

The control strategy uses the same reference (synchronized sinusoidal signal) as the conventional while the carrier triangle is a modified one. In the high frequency triangular wave any two adjacent cycles can be grouped either "W" shape or "M" shape (named as cycle group). The difference in pulse widths resulting from "W" cycle group and "M" cycle group with the low (output) frequency reference sine wave in different sections can be easily understood.

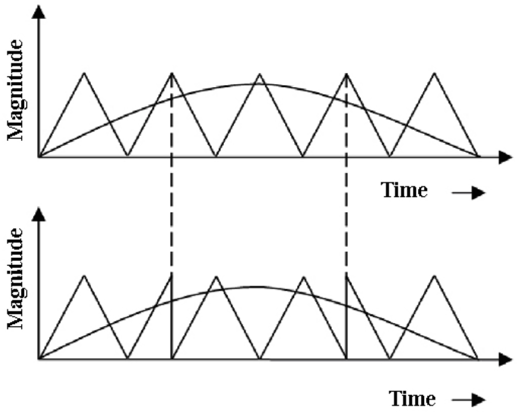


Fig. 3. W to M conversion [$M_f = 5\,(\text{odd})$].

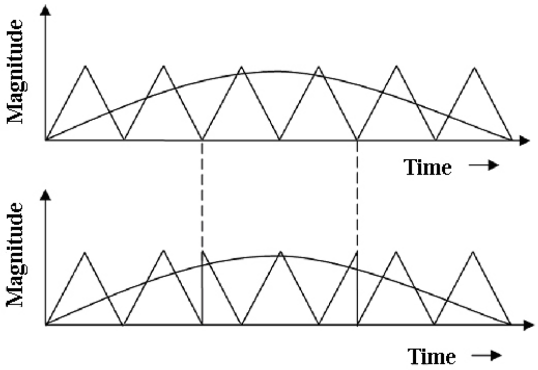
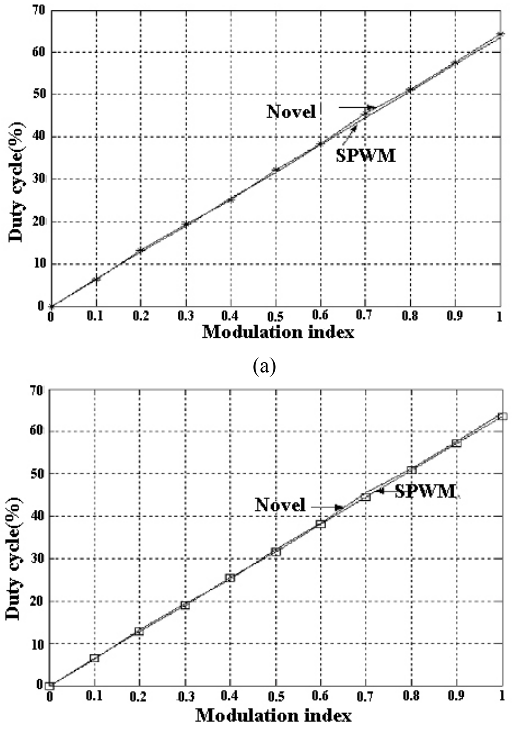


Fig. 4. M to W conversion [$M_f = 6\,(\text{even})$].

Better THD and enhanced fundamental component demand wider center pulses and shorter pulses in both sides. Hence, conversion of the carrier cycle group (M to W)/(W to M) may help the scheme. Fig. 3 shows typical conversion of W cycle group to M while Fig. 4 shows M cycle group to W. The center region of reference wave requires W to M conversion while the remaining regions require the other. Besides, an optimal case may need n number of such conversions. Influence of the changes in indices is predicted using mathematical relations and a simulation study.

It is evident that for odd frequency ratio, M_f (hence odd number of triangle) W to M conversion and for even M_f (hence even number of triangle) M to W conversion will be beneficial/possible conversion in centre region. This is due to the fact that in odd M_f, a W cycle group can only be a middle cycle group while in even M_f it can be only an M cycle group. Figs. 3 and 4 explain these constrains for odd and even M_f instances, respectively. In both cases, conversion leads to an increase in the PWM pulse width in the selected region. There is an increase in the pulse numbers by one in the selected region while the other regions remain unaffected. There may be more number of such a possible combination not only in the center region but also in the remaining regions. Any odd M_f has $(M_f - 1)/2$ cycle groups and all the even M_f values have $(M_f/2 - 1)$ cycle groups. Optimization of carrier modification in the novel method (the number of possible cycle group changes), depends on the number of triangles (M_f). If the number of triangle is 8, then the number of cycle groups is 3. The possible carrier pattern may be MMM, MWM, WMW and WWW. Any one of the



(a)

(b)

Fig. 5. Modulation depth versus duty cycle, (a) $M_f = 10$, and (b) $M_f = 20$.

above combinations may also yield better results. The number of cycle groups for even M_f can be obtained as follows

$$\begin{aligned} &\frac{M_f}{2}-1 \text{ for } M_f = 4, 8, 12, 16, 20, 24, \ldots 4n \\ &\frac{M_f}{2} \text{ for } M_f = 6, 10, 14, 18, 22, \ldots 4n+2 \end{aligned} \tag{1}$$

where, n is 1, 2, 3 ….

B. Simulation Study

The performance of proposed method is evaluated using MATLAB®/Simulink® software package. The fundamental magnitude, THD and output spectrum are compared with SPWM results for similar cases. Other control/performance parameters like number of pulses, duty cycle and inverter gain are also analyzed. Thus, the evolution of crossover points and duty cycle will result in a true appraisal of the scheme. The results of simulation for 400 V V_{dc} and unity M_f are listed in Tables II and III for odd and even number of triangles.

Tabulated entries reveal the effectiveness of the scheme in even M_f compared to that of odd M_f. In the case of odd M_f, though the scheme fails to work, it does not deteriorate the performance. It shows either a marginal difference or the same value when compared to SPWM. But even M_f gives higher fundamental than the SPWM for entire range of modulation depth.

1) Duty Cycle

The number of pulses per cycle, width of the individual pulses and duty cycle can be determined for a given M_a and M_f. M-file program is coded with a mathematical background for generating crossover points, pulse width and duty cycle. Fig. 5 shows that the variation of duty cycle while varying modulation index for frequency ratio 10 and 20 for SPWM and novel schemes.

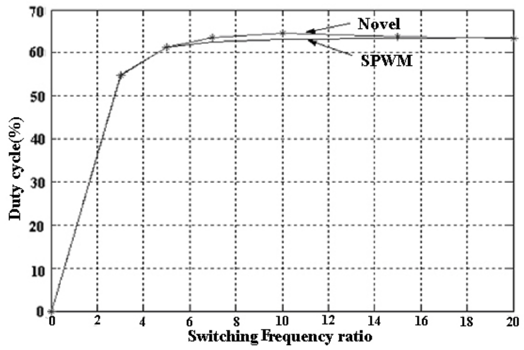


Fig. 6. Frequency ratio versus duty cycle for $M_a = 1$.

TABLE II
COMPARISON OF FUNDAMENTAL AND THD, ODD M_f

Odd M_f	SPWM		Novel	
	Fund.	THD	Fund.	THD
9	284.5	50.5	284.3	50.2
11	285.1	51.3	282.7	51.0
13	282.8	51.6	282.3	51.1
15	282.1	51.7	283.1	51.3
17	284.7	51.8	285.8	51.3
19	277.8	51.9	277.7	51.3
21	284.1	51.9	284.2	51.3

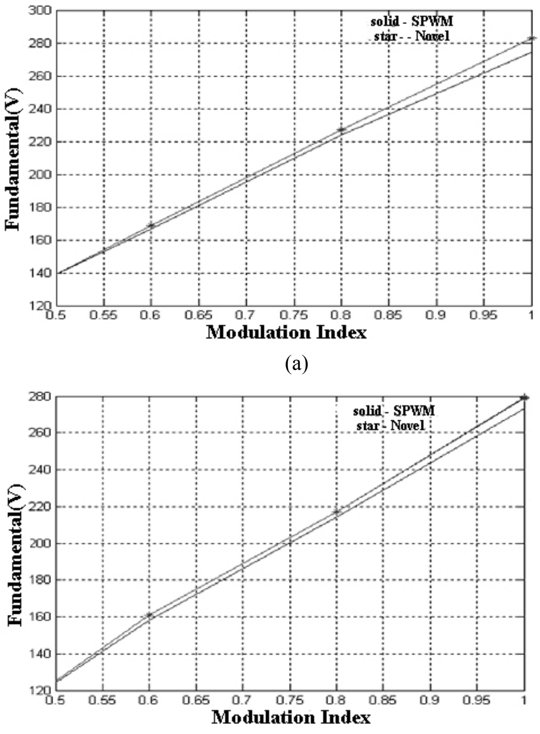
TABLE III
COMPARISON OF FUNDAMENTAL AND THD, EVEN M_f

Even M_f	SPWM		Novel	
	Fund.	THD	Fund.	THD
8	285.1	50	287.0	48
10	274.3	51	283.4	50
20	273.2	52	279.4	51
30	281.6	52	286.6	51
40	287.3	52	289.3	51
50	248.7	52	250.7	51

Fig. 5 shows that duty cycle varies linearly with the modulating index (for $M_a < 1$) both for SPWM and novel technique. The MCPWM provides considerable improvement in duty cycle over the whole range of M_a. From Fig. 6, it is observed that duty cycle depends on M_f which is contradictory to conventional belief. The dependency is more in a low range of M_f. The shape of the curve in both cases is identical. It follows MCPWM retains the basic property of SPWM. However, for values of M_f in the range 6 to 13, MCPWM exhibits better duty cycle.

2) Fundamental and THD

The variation of fundamental as a function of modulation depth is shown in Fig. 7 for frequency ratios of 10 and 20. Though the fundamental component for MCPWM is higher than that for the SPWM technique over the entire range of modulation depth, its influence is significant in the higher values of modulation depth. Fig. 8 shows the benefit of the proposed scheme in the variation in the fundamental for carrier frequency changes, up to $M_f = 40$. The inverter output voltage range increases by approximately 4 percent before overmodulation and pulse-dropping. In addition the linearity which is retained between the fundamental voltage and modulation depth



(a)

(b)

Fig. 7. Fundamental versus modulation index, (a) $M_f = 10$, and (b) $M_f = 20$.

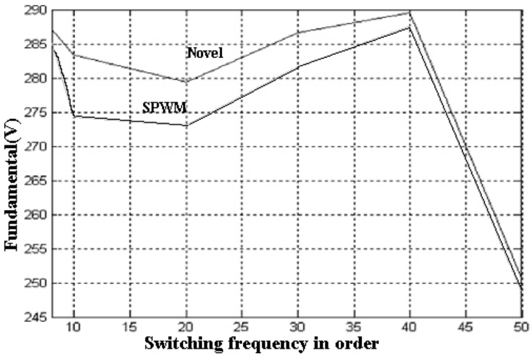


Fig. 8. Switching frequency versus fundamental for $M_a = 1$.

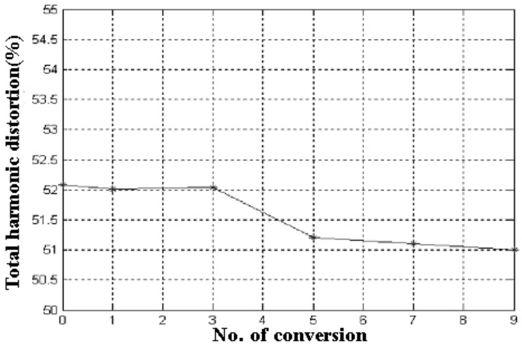


Fig. 9. Influence of the number of cycle group conversion.

provides a simple means for controlling the output voltage.

Fig. 9 depicts the relation between THD and number of cycle group conversions for the frequency ratio 20 (maximum possible cycle group conversion is 9). It follows that the MCPWM is guaranteed for fundamental enhancement.

Figs. 10 and 11 reveal that the variation of THD as a function of modulation depth and switching frequency for constant frequency ratio and modulation depth, respectively. It can be noted that the THD decreases as the modulation depth increases in both cases. Improvement in THD in the case of MCPWM is more in the lower range of modulation depth. Betterment of THD due to carrier frequency variation is almost constant. A comparison of THD for the SPWM and MCPWM as a function of fundamental voltage is shown in Fig. 12 for frequency ratio 10. It shows that the MCPWM produces lower THD for any value of the required fundamental. It is interesting to note that the proposed scheme offers reduced distortions

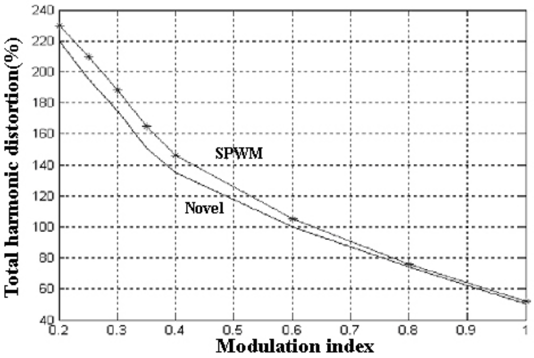


Fig. 10. Modulation index versus THD for $M_f = 10$.

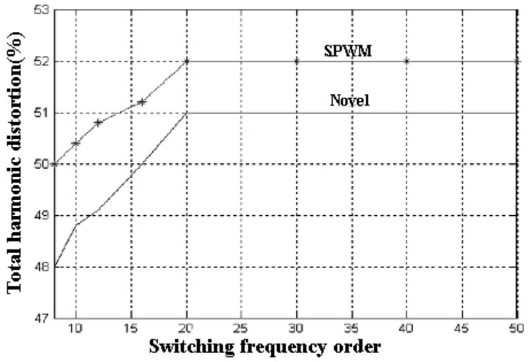


Fig. 11. Switching frequency Vs THD for $M_a = 1$.

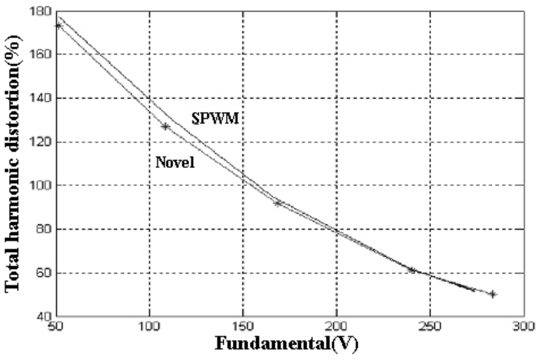
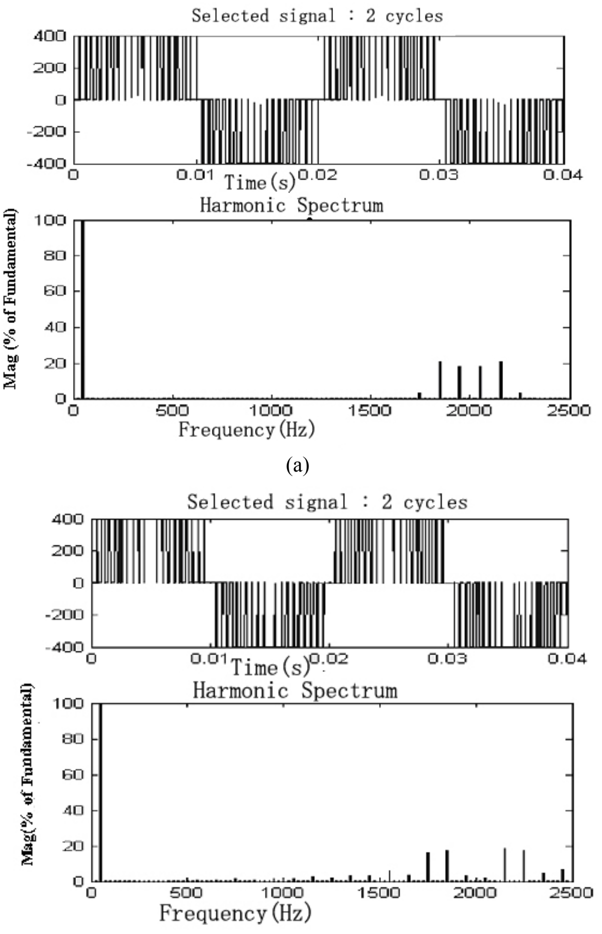


Fig. 12. Fundamental Vs THD for $M_a = 1$ and $M_f = 10$.

TABLE IV
FUNDAMENTAL AND HARMONICS MAGNITUDE

Harmonic Order(h)	V_h (SPWM)	V_h (MCPWM)
35	3.64	16.27
37	21.27	17.01
39	18.01	3.52
41	18.27	2.73
43	23.23	18.31
45	4.12	17.23
V_1	273.2	279.4



(a)

(b)

Fig. 13. Output voltage waveform and harmonic spectrum, (a) SPWM, and (b) MCPWM.

note that the proposed scheme offers reduced distortions even at low modulation depths.

3) Spectrum and Dominant Harmonics

MCPWM scheme achieves fundamental voltage values of range which can only be obtained by overmodulation, if a conventional scheme is adopted. Fig. 13 shows that output voltage waveforms and harmonic spectrums of SPWM and MCPWM for $M_a = 1$, $M_f = 20$, and $V_{dc} = 400$ V. Table IV gives the fundamental component absolute value and the magnitude of other harmonics (V_h) as percentage of fundamental, V_1 in both cases for the same conditions. The fundamental value obtained from SPWM schemes at the limit of voltage linearity limit ($M_a = 1$) is 273.2 V.

The ability of not introducing low-order harmonics for a higher (overmodulated with respect to the original sine PWM techniques) fundamental component (279.4 V) can be seen more precisely from Fig. 13, which compares the harmonic content in the output voltage of MCPWM with SPWM. The Figure and Table illustrate that the percentage of harmonic magnitude in MCPWM is lower than in the SPWM except for the orders 35th and 45th. The MCPWM technique extracts better performance in harmonic elimination and reduces higher order harmonics magnitude over sinusoidal PWM strategy at any range of switching frequencies. The bar diagram as shown in Fig. 14 highlights that the magnitudes that are achieved in the proposed strategy at particular switching frequency can only be achieved for modulation indices greater than one in a conventional scheme.

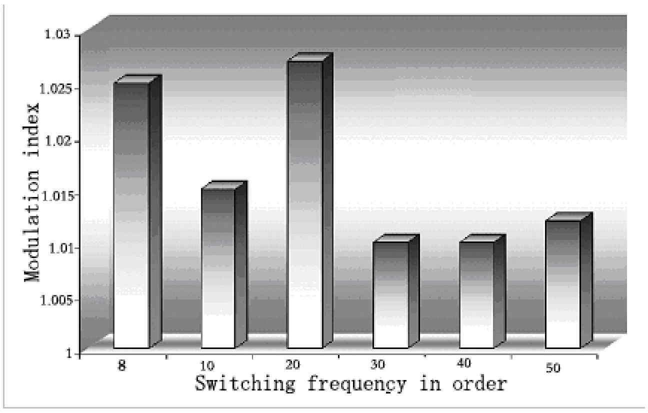


Fig. 14. Modulation depth required in SPWM.

4) Comparison with Harmonic Injection PWM Methods

The fundamental amplitude in the PWM output waveform is smaller than that of the rectangular waveform. The ratio of fundamental voltage in the output waveform to the direct supply voltage must be higher. In the conventional SPWM of three-phase inverter, the ratio of the fundamental component of the maximum line-to-line voltage to the direct supply voltage is 0.87. This value indicates poor utilization of the dc power supply. The third harmonic injection PWM (THIPWM) technique to increase the amplitude of the fundamental component was proposed in [15], where a third harmonic wave is added to the three-phase sinusoidal modulating wave. However, this technique generates a substantial ac term third-harmonic component (17 percent) on line-to-neutral basis. This disallows the use of neutral-to-neutral connections (if required) and loses the property of decoupled (individual) control of each one of the three inverter phases. The optimum value of third harmonics to be added was provided in [16]. Analytical expression for the reference waveform in THIPWM is

$$y = 1.155(\sin \omega t + \frac{1}{6} \sin 3\omega t)\,. \qquad (2)$$

The triplen harmonic injection PWM (TRIPWM) is a variation of the previously discussed THIPWM. In TRIPWM, the modulation signal for three-phase PWM inverter is obtained by adding the harmonic components of integer multiples of 3 to the three-phase sine waves [1], [17]. Analytical expression for the reference waveform in TRIPWM is

$$y = 1.15\sin(\omega t) + 0.27\sin(3\omega t) - 0.029\sin(9\omega t)\,. \qquad (3)$$

It appears logical that any synchronous PWM for single-phase inverter based on carrier modification should have appropriateness to work well in three-phase inverter. Also, the reference modification in harmonic injection PWM methods and carrier modification in the proposed MCPWM aim at increasing the fundamental through increase in the pulse width around the centre region of the reference. As the aim both the modifications are same, *amalgamation of both reference and carrier modifications will improve the situation further*. On the basis of this intuitive notion, it is logical to amalgamate the MCPWM with TRIPWM

TABLE V
EFFECT OF MCPWM AMALGAMATION IN HARMONIC INJECTION PWM METHODS, ($M_f = 10$)

Technique	V_{LL} (V)	V_{Ph} (V)	V_3 (% of V_{Ph})	THD
SPWM	239.7	138.4	1.30	65.63
MCPWM	246.1	142.5	0.56	64.71
TRIPWM	261.7	154.5	19.13	62.21
TRI-MCPWM	264.7	156.5	18.49	61.81
THIPWM	267.1	156.9	12.43	58.41
THI-MCPWM	267.6	157.2	11.58	58.81

TABLE VI
EFFECT OF MCPWM AMALGAMATION IN HARMONIC INJECTION PWM METHODS, ($M_f = 20$)

Technique	V_{LL} (V)	V_{Ph} (V)	V_3 (% of V_{Ph})	THD
SPWM	236.4	136.4	0.49	62.47
MCPWM	240.5	139.1	2.12	61.48
TRIPWM	257.9	151.8	17.15	59.38
TRI-MCPWM	258.6	151.9	16.95	58.21
THIPWM	260.4	153.0	14.17	55.82
THI-MCPWM	261.0	153.0	14.00	55.52

TABLE VII
EFFECT OF MCPWM AMALGAMATION IN HARMONIC INJECTION PWM METHODS, ($M_f = 30$)

Technique	V_{LL} (V)	V_{Ph} (V)	V_3 (% of V_{Ph})	THD
SPWM	239.7	137.9	2.20	58.44
MCPWM	245.9	142.6	1.44	54.45
TRIPWM	265.7	158.2	19.12	56.85
TRI-MCPWM	266.1	158.2	18.85	56.59
THIPWM	266.9	157.7	10.98	52.48
THI-MCPWM	265.9	156.9	11.21	52.13

(TRI-MCPWM) and THIPW (THI-MCPWM). The betterment of amalgamated performance is proved for three-phase inverter circuit by simulation and compared in Tables V, VI, VII for the frequency ratio values 10, 20 and 30, respectively. The output line and phase voltages, percentage of third harmonic content in output and THD are used here as a basis for comparison of switching strategies. The methods are arranged in the ascending order of their performance merit. The THIPWM amalgamation with MCPWM performs well when compared to other cases.

IV. GENERATION OF MCPWM PULSES

The proposed modified carrier is an incommensurable and non-periodic function. Hence implementation of the proposed carrier in analog circuits is rather complex. Hence the SPWM and MCPWM patterns are implemented digitally in a general purpose Intel 8-bit microprocessor (Intel 8085). In the past, many attempts have been made to develop microprocessor based power electronic systems in particular much effort has been spent towards digitization of modulating function (MF) based pulse width modulation methods, to replace the traditional analog circuitry with microprocessor-based systems [18], [19]. Most of the algorithms proposed, the basic hardware and software are modified depending upon the technique of realization and type of PWM waveform. Ideally, one would wish to reproduce the desired characteristics of natural-sampled SPWM and it modified forms on-line and in real time without any external circuitry by a competent algorithm.

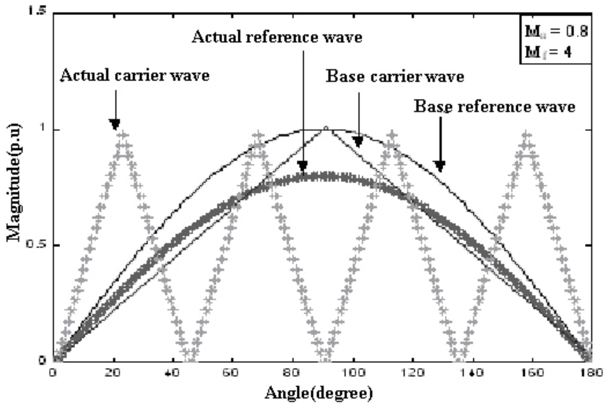
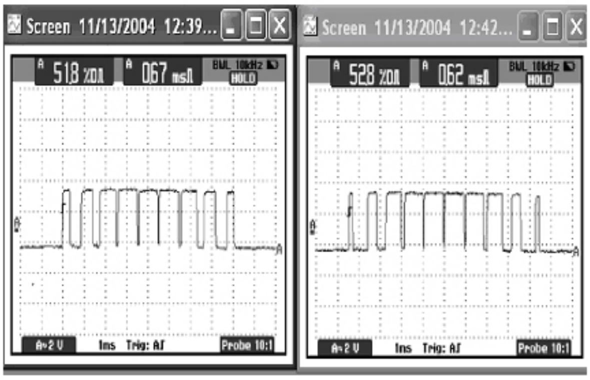


Fig. 15. Obtaining carrier and reference in TRR.



(a) (b)

Fig. 16. Pulse distribution for $M_a = 1$ and M_f=10, (a) SPWM, and (b) Novel.

PWM patterns for SPWM and MCPWM are done through the developed novel unified algorithm called *Time Ratio Recursion* (*TRR*). The proposed algorithm is basically a pseudo-real time algorithm, which generates PWM pattern off-line then displays them in on-line for the fixed modulation depth (M_a) and frequency ratio (M_f) until new combination of them is demanded. The concept of the proposed algorithm is carrier wave of any frequency can be achieved through fetching rate of the triangle pattern while reference of any magnitude is through the multiplying factor.

To describe the wave of any kind, a simple and practical method is the look-up table (LUT) method, wherein the amplitude of the waveform is digitized at discrete points along the phase axis, and the digital values are stored in sequentially addressed locations. The digitized values (8-bit words) of the sine wave (SW) and the triangular wave (TW) with the maximum value set to 1 p.u. of the peak amplitude are stored from 0 to π at an interval of one degree for each wave (180_{10}/$B4_H$ samples), which is adequate for continued generation of the periodic waveforms. The digitized stored values of sine waveform for unity modulation depth and output frequency is called base reference wave while digitized triangular of frequency and amplitude same as base reference is called base carrier. Actual reference for PWM pattern generation is obtained by multiplying base reference by the required modulation index while the actual carrier is obtained through increasing the fetching rate by required frequency ratio times.

Implementation of the proposed modified triangular carrier needs reverse fetching of the carrier LUT values in the sections where “M” to “W” conversion is required, i.e., reading from 90° to 0° instead of 0° to 90° with the same fetching rate. Representative pulses for a half output cycle resulted from TRR algorithm are shown in Figs. 16(a) and 16(b) for SPWM and MCPWM, respectively, for $M_a = 0.8$ and $M_f = 1\,\text{kHz}$ with one cycle group conversion. The differences in the pulse widths and the positions are clearly understood. The increase in duty cycle value also be evidenced as 51.8% and 52.8% for SPWM and MCPWM methods, respectively. Irrespective of number of cycle group conversions the MCPWM method results in increase pulse count just by one, which will not cause considerable account in device losses and hence efficiency [8].

V. CONCLUSION

The result of the proposed work shows that it is feasible to improve the fundamental for the given switching frequency in a single-phase full-bridge inverter. The linear relationship (property of SPWM) between the fundamental and modulation depth M_a is retained. It extends the voltage range by approximately 4 percent before overmodulation and pulse-dropping. Simulation results validate the improved spectral performance of the proposed scheme over a standard SPWM scheme at both low and high modulation indices. The main advantage of this approach is that it adopts a consistent strategy for the entire range of modulation index i.e. it does not require different switching strategies at different levels of modulation index. The scheme also eliminates/reduces lower order harmonics for any value of voltage and hence will strive to work as an effective alternative to overmodulation. The appreciable improvement in THD in the lower range of modulation depth attracts drive applications where low speed operation is required. The reduced distortions even at low modulation depth provide scope for proposed scheme not only when higher fundamental demanded and also obtaining low fundamental values. However, the analysis indicates that the proposed technique may marginally increase the conduction and switching losses. The extension of the proposed PWM strategy to three-phase PWM inverters and amalgamation with harmonic injection PWM methods (THIWPM and TRIPWM) may widen the application range of the technique; including drives, uninterruptible power supplies, static frequency changers, etc.

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