Five-Level Selective Harmonic Elimination PWM Strategies and Multicarrier Phase-Shifted Sinusoidal PWM: A Comparison

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Abstract—The multicarrier phase-shifted sinusoidal pulse-width modulation (MPS-SPWM) technique is well-known for its important advantage of offering an increased overall bandwidth as the number of carriers multiplied with their equal frequency directly controls the location of the dominant harmonics. In this paper, a five-level (line-to-neutral) multilevel selective harmonic elimination PWM (MSHE-PWM) strategy based on an equal number of switching transitions when compared against the previously mentioned technique is proposed. It is assumed that the four triangular carriers of the MPS-SPWM method have nine per unit frequency resulting in seventeen switching transitions for every quarter period. Requesting the same number of transitions from the MSHE-PWM allows the control of sixteen non-triplen harmonics. It is confirmed that the proposed MSHE-PWM offers significantly higher converter bandwidth along with higher modulation operating range. Selected results are presented to confirm the effectiveness of the proposed technique.

I. INTRODUCTION

Selective harmonic elimination pulse-width modulation techniques (SHE-PWM) have been mainly developed for two or three-level schemes [1]-[12]. The main challenge associated with such techniques is to obtain the analytical solutions of non-linear transcendental equations that contain trigonometric terms which naturally exhibit multiple solutions [5]. There have been many approaches to this problem reported in the technical literature including: sequential homotopy-based computation [6], resultants theory [7], optimization search [8], Walsh functions [9]-[10] and other optimal methods [9]. The bipolar waveform has been treated in detail in [12] where a minimization technique is employed along with a biased optimization search method to get the multiple sets as predicted in [6].

On the other hand, multilevel converters based on solid-state have been investigated for more than three decades. Initially, when the switching frequency was restricted to line frequency, the generic question associated with the SHE-PWM approach has mainly been the way the staircase multilevel waveform is generated in order to control the amplitude of the fundamental frequency and eliminate the maximum number of harmonics from the waveform [13]. A generalized staircase waveform suitable for a multilevel converter and system is shown in Fig. 1, where the transition angles are linked with the level change. In a generic definition this does include non-equal DC levels of course and the equal DC sources case is a subset.

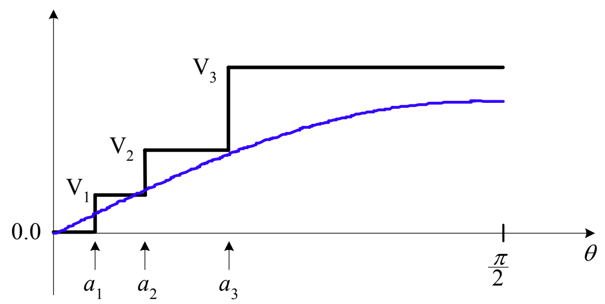

Fig. 1. The generalized staircase waveform suitable for multilevel systems and related angles of transition between the various voltage levels.

Recently a number of technical papers have appeared addressing the multilevel waveform using similar theories used previously for the bipolar (two-level) and unipolar (three-level) waveforms. Specifically, the theory of resultants and its performance for a multilevel staircase waveform was reported in [14]. A unified approach was presented in [15]. More recently, the use of symmetric polynomials is combined with the resultant theory for a multilevel converter [16]. Previous work [14] has shown that the transcendental equations characterizing the harmonic content can be converted to polynomial equations which are then solved using the method of resultants from elimination theory. A difficulty with this approach [14], as the authors suggest [16], is that when there are several DC sources, the degrees of the polynomials are quite large, thus making the computational burden of their resultant polynomials (as required by elimination theory) quite high. In [16], the theory of symmetric polynomials is exploited to reduce the degree of the polynomial equations that must be solved which in turn greatly reduces the computational burden.

Multilevel SHE-PWM systems have been controlled using the unipolar case, where the waveform takes a positive, a negative and a zero value, and phase-shifted techniques are used to build multilevel systems [17]. Other approaches have also been reported including one where the harmonic elimination is combined with a programmed method [18] and another where a criterion based on power equalization between various cascaded connected H-bridge multilevel converters is used to obtain the angles of the harmonic elimination method [19].

The multicarrier PS-SPWM has been used to increase the bandwidth of the various converters. This can be traced back in the 1980s in a conference [20] and then a journal publication appeared [21]. It was then used in many other works as it provided an opportunity to cancel a number of harmonics if the phase-shift between the numerous carriers is chosen carefully.

However, although the MPS-SPWM technique has been extensively used for multilevel systems, no comparison with a MSHE-PWM technique has been reported to clarify the performance of each method against each other. For instance, higher gain and improved bandwidth for the programmed SHE-PWM techniques have been reported but these gains were analyzed only for the two-level systems [4]. So far, there exists limited information reported if such superior performance can also be attributed to the MSHE-PWM methods. Moreover, thus far there has been no paper published that presents a complete set of angles for high frequency multilevel waveform for all modulation indices.

The objective of this paper is first to propose a MSHE-PWM strategy defined at five-levels as shown in Fig. 2. The various switching angles as a function of the modulation index are also presented. The proposed technique is then compared against the well-known MPS-SPWM technique using four carriers in order to create a five-level line-to-neutral switching pattern.

The paper is organized as follows. Section II presents in detail the proposed five-level SHE-PWM. In Section III the PS-SPWM technique suitable for the five-level system is also briefly presented. The comparison between the two techniques is discussed in Section IV and conclusions are summarized in Section V.

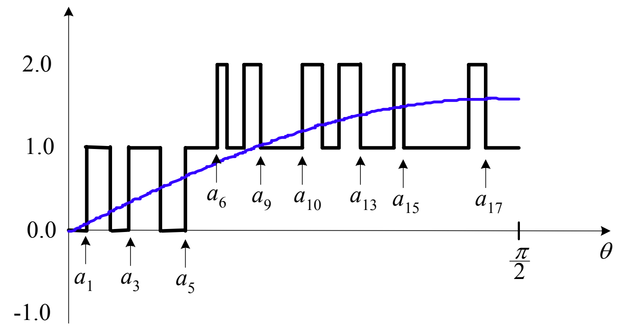

Fig. 2. A five-level defined (line-to-neutral) MSHE-PWM waveform shown for a distribution ratio of 5/12 (k=5, m=12, and N=k+m=17)

II. THE FIVE-LEVEL MSHE-PWM WAVEFORM

The proposed five-level MSHE-PWM strategy is defined according to the waveform shown in Fig. 2 and represents the line-to-neutral waveform of the converter. The number of levels of the waveform is assumed to be five, i.e., 1p.u., 2p.u., 0p.u., -1p.u. and -2p.u. Let N be the number of total switching transitions (angles) of the waveform sought within the quarter of the period of the waveform. This number can be either odd or even. However, there are restrictions once it is chosen. For this paper, N is chosen to be an odd number. Let k be the number of the switching transitions placed between the 0p.u. level and the 1p.u. This number can only be an odd number since the first switching transition is chosen to be from 0p.u. to 1p.u. level. Let m be the number of the remaining switching transitions placed between 1p.u. and 2p.u. levels. This number can be either even or odd depending upon N. In this case, since N has chosen to be odd and k is only odd, m can only be even.

Then, for the proposed MSHE-PWM strategy, k can only be an odd number

$$k = 1, 3, ..., N \tag{1}$$

m can only be an even number since N has been chosen to be an odd number, hence

$$m = 0, 2, ..., N-1 \tag{2}$$

and the total sum of both k and m must always be equal to the maximum switching transitions, hence

$$N = k + m \tag{3}$$

For any ratio of k/m then a different set of transcendental equations describing the Fourier equations linked to the amplitude of the harmonics that can be eliminated needs to be written down. The idea here is the classic SHE method that tries to find switching angles in order to eliminate a number of harmonics and control simultaneously the fundamental component. The challenge of the proposed method is that for the first time such a method is applied to a "true" multilevel waveform, i.e. five-level waveform (Fig. 2). The typical half-wave and quarter-wave symmetries are respected for the waveform, i.e., simply when the switching angles for all modulation indices are obtained for the angles between zero and $\pi/2$, the usual reflection occurs to find the rest of the angles. Since there are N switching angles (i.e., α_1, α_2, α_3,.... α_i, where $i = N$), $N-1$ harmonics can be eliminated if solutions can be found. In a three-phase inverter, for harmonics to be eliminated from the waveform they are assumed to be non-triplen odd harmonics (i.e., fifth, seventh, 11th, 13th, n-th where $n = 3N-2$). The strategy then relies on the structure of the power circuit in order to remove the non-triplen ones from the line-to-line voltage waveforms.

In a generalized form, the set of equations that need to be solved is as follows:

$$M = \sum_{i=1}^{k}\left((-1)^{i-1}\cos(\alpha_i)\right) + \sum_{i=k+1}^{k+m}\left((-1)^{i-(1+k)}\cos(\alpha_i)\right) \tag{4}$$

$$0 = \sum_{i=1}^{k}\left((-1)^{i-1}\cos(5\alpha_i)\right) + \sum_{i=k+1}^{k+m}\left((-1)^{i-(1+k)}\cos(5\alpha_i)\right) \tag{5}$$

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$$0=\sum_{i=1}^{k}\left((-1)^{i-1}\cos(n\alpha_i)\right)+\sum_{i=k+1}^{k+m}\left((-1)^{i-(1+k)}\cos(n\alpha_i)\right) \tag{6}$$

where

$$n=3N-2 \tag{7}$$

$$0\le M\le 2 \tag{8}$$

If V_1 is the amplitude of the fundamental component to be generated, then

$$V_1=\frac{4M}{\pi} \tag{9}$$

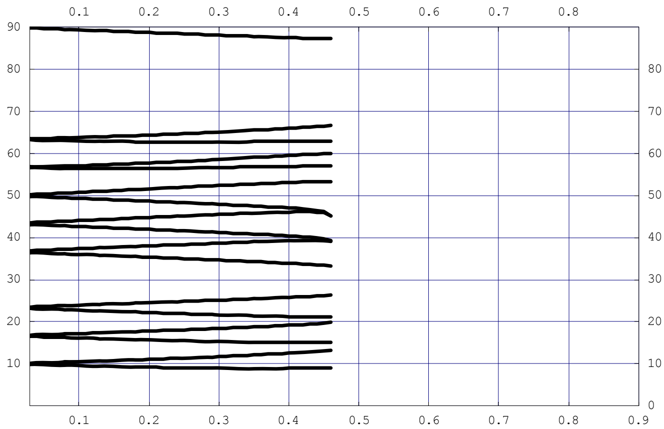
when $M=2$ the square-waveform of 2p.u. amplitude can generate $8/\pi$ per unit maximum value at fundamental frequency.

The minimization technique proposed in [8] has been applied and software is used to investigate the method [22]. The distribution ratio varies for each case where a new set of equations describing the new waveform are written. The equations relating to the minimization of the transcendental equations describing the Fourier coefficients are then solved. The regions where solutions exist for a given distribution ratio are summarized in Table 1. For this paper, N=17. However, this number and the various ratios can be changed as desired and the minimization method [8] would provide the respective solutions provided they exist.

In this paper, a selected set of solutions for every region are reported although many more might exist. Therefore, it is beyond the scope of this paper to treat the cases where multiple sets of solutions can be found, although some overlap and multiple solutions are also reported. The aim here is to find solutions that provide PWM waveform realization for the entire region of modulation indices. The investigation at this stage has not gone to the point where such solutions are evaluated to identify potential sets that offer better performance.

It should be noted that the result obtained from the proposed method when the ratio is chosen to be 17/0 provides solutions for all modulation indices up to 0.9, which has been reported in other cases to be the maximum attainable value for similar approaches (i.e. the three-level or unipolar waveform) [7]. This implies that a three-level technique covering this region can be implemented and the result confirms that there are more than one set of solutions. The first is a discontinuous set and the second covers the entire range. Further results for all combinations of ratios are plotted in Fig. 3. The last harmonic that can be eliminated according to equations (4)-(6) is the 49p.u. and this is confirmed in Fig. 4.

Specifically, Fig. 4(b) shows that this waveform has only multiple of triplen harmonics which are cancelled out in a three-phase system for the line-to-line waveforms. This is confirmed and the normalized line-to-line voltage waveform is shown in Fig. 4(c). The bandwidth of the normalized line-to-line voltage waveform is proved to be according to the



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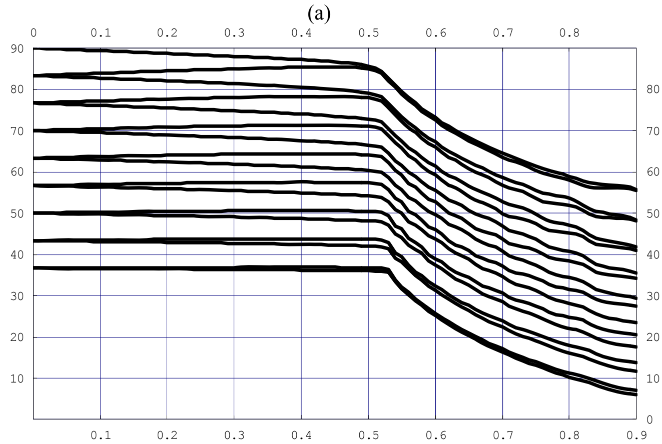

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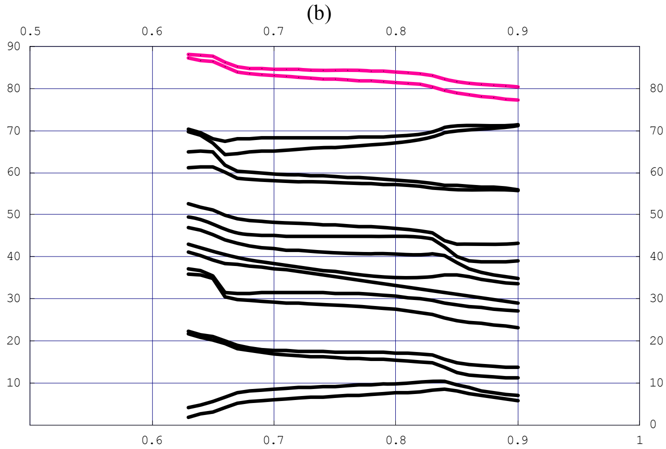

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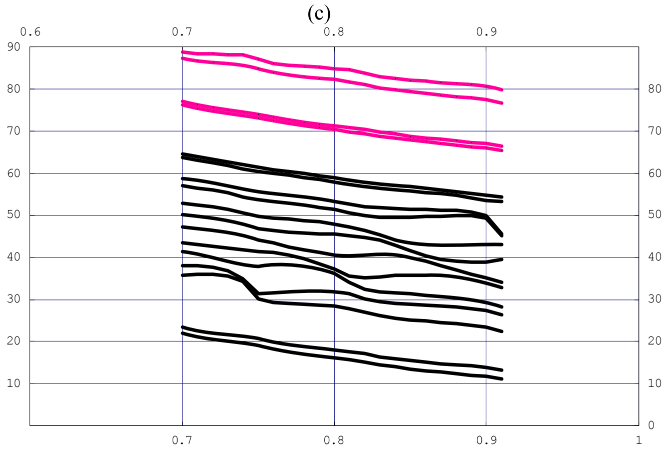

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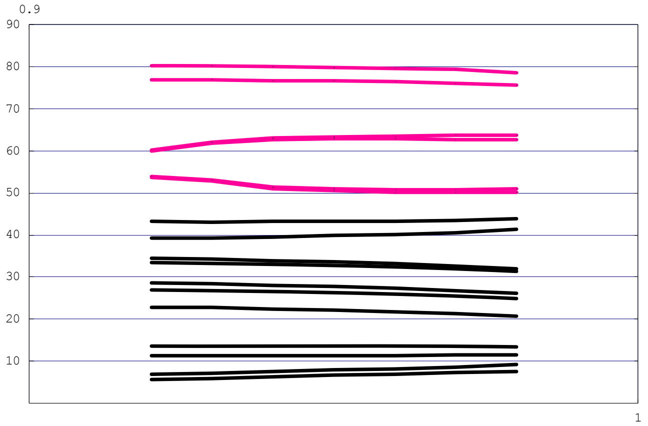
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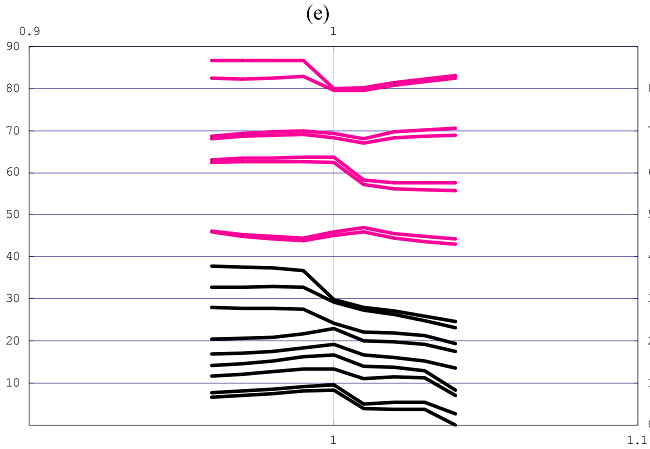
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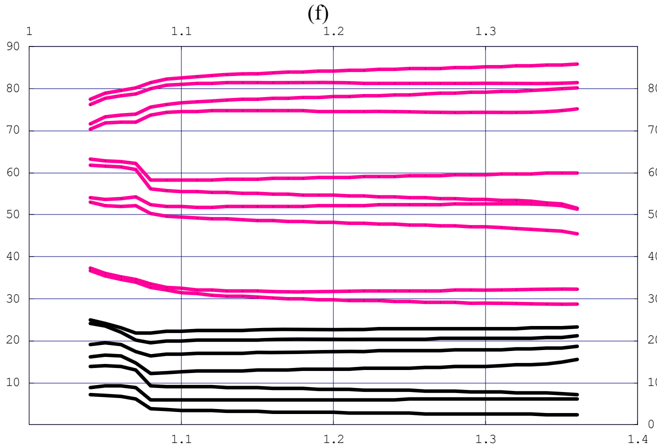
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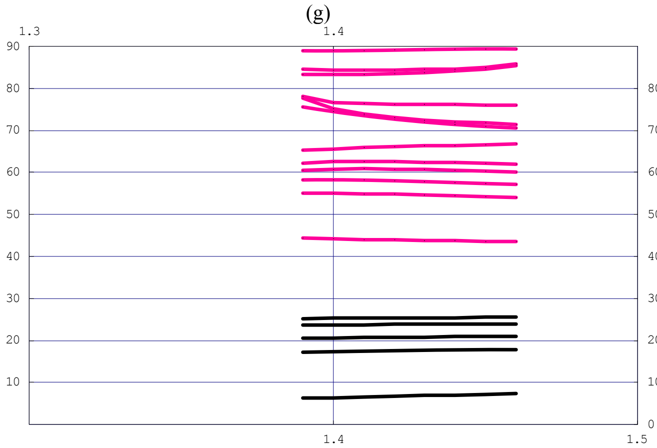
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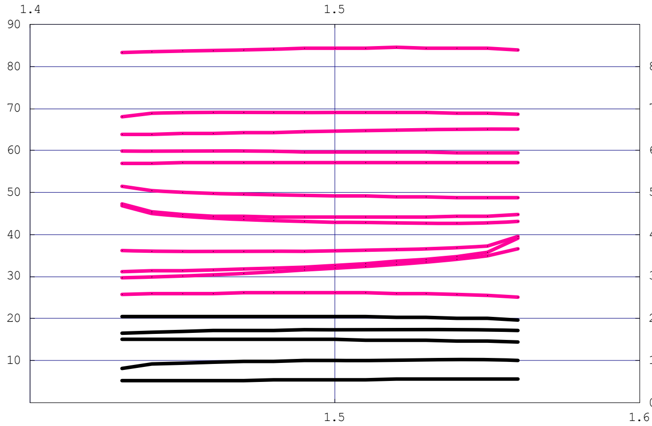
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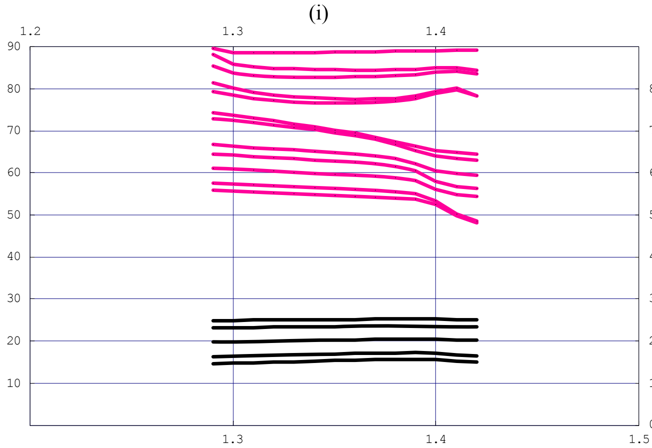
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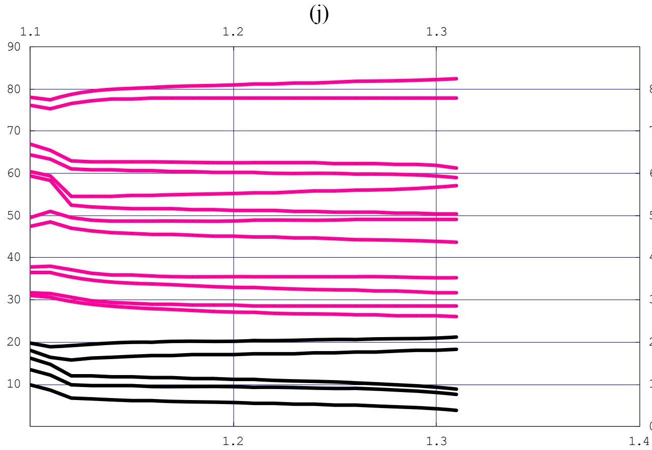
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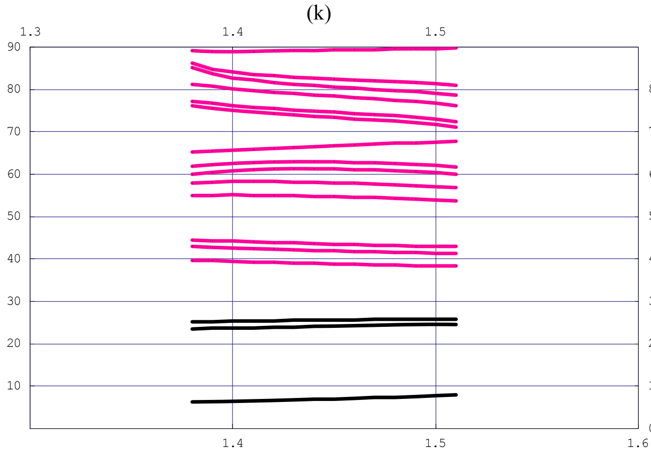
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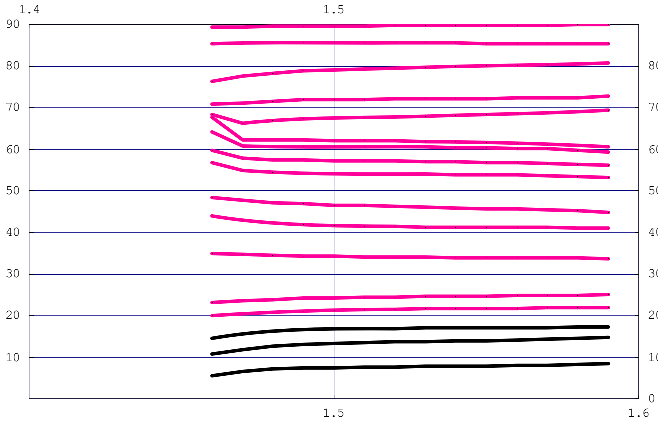

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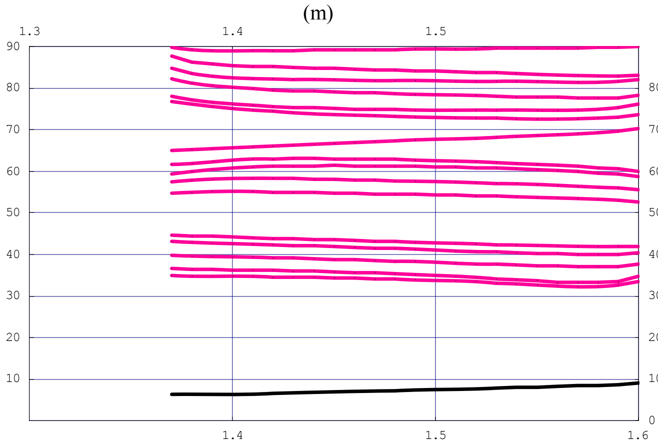
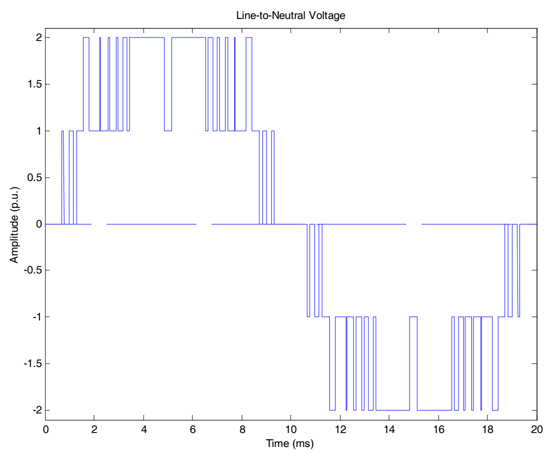


(n)

Fig. 3. Switching angles for the various ratios of *k/m* and cases which are also summarized in Table 1 for *N*=17. (a) Case I: 17/0 (Set 1, $0 \le M \le 0.46$). (b) Case I: 17/0 (Set 2, $0 \le M \le 0.9$). (c) Case II: 15/2 ($0.63 \le M \le 0.9$). (d) Case III: 13/4 ($0.7 \le M \le 0.91$). (e) Case IV: 11/6 ($0.92 \le M \le 0.98$). (f) Case V: 9/8 ($0.96 \le M \le 1.04$). (g) Case VI: 7/10 ($1.04 \le M \le 1.36$). (h) Case VII: 5/12 (Set 1, $1.39 \le M \le 1.46$). (i) Case VII: 5/12 (Set 2, $1.43 \le M \le 1.56$). (j) Case VII: 5/12 (Set 3, $1.29 \le M \le 1.42$) (k) Case VII: 3/14 (Set 4, $1.1 \le M \le 1.31$). (l) Case VIII: 3/14 (Set 1, $1.38 \le M \le 1.51$). (m) Case VIII: 3/14 (Set 2, $1.46 \le M \le 1.59$). (n) Case IX: 1/16 ($1.37 \le M \le 1.6$).

theory, which is that the harmonics up to the 49p.u. are all zero. Since the 51p.u. harmonic is a triplen one, the first significant harmonic turns out to be the 53p.u. (Fig. 4(d)).



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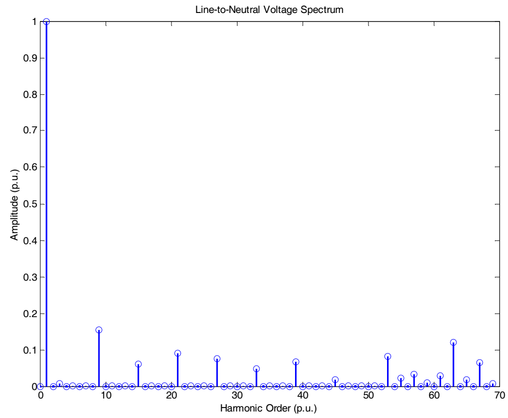

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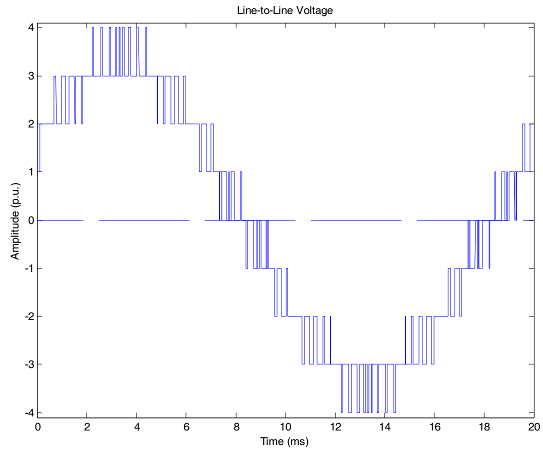

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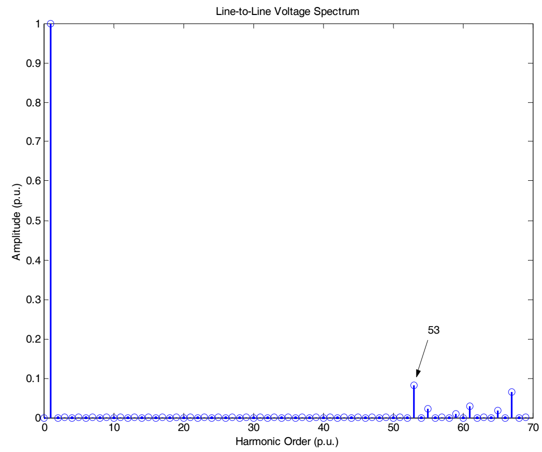

(d)

Fig. 4. Selected waveforms implemented with the switching angle solutions given by the proposed method, $N = 17$, non-triplen harmonics to be eliminated up to 49p.u. ($n = 3N - 2$), and taken from the case where $k/m = 5/12$, Set 3). (a) Line-to-neutral voltage waveform normalized over M ($M = 1.5$)). (b) Spectrum of the normalized line-to-neutral voltage waveform ($M = 1.5$). (c) Line-to-line voltage waveforms normalized over M ($M = 1.5$). (d) Spectrum of the normalized line-to-line voltage waveform ($M = 1.5$).

Table 1: Summary of regions of the modulation index M where solutions for all switching angles exist as a relationship to the variable ratio of distribution of the switching angles between the multiple levels (k/m).

k/m	Region	*k/m*	Region
Case I: 17/0	$0 \le M \le 0.46$ (Set 1) $0 \le M \le 0.9$ (Set 2)	Case VI: 7/10	$1.04 \le M \le 1.36$
Case II: 15/2	$0.63 \le M \le 0.9$	Case VII: 5/12	$1.39 \le M \le 1.46$ (Set 1) $1.43 \le M \le 1.56$ (Set 2) $1.29 \le M \le 1.42$ (Set 3) $1.1 \le M \le 1.31$ (Set 4)
Case III: 13/4	$0.7 \le M \le 0.91$	Case VIII: 3/14	$1.38 \le M \le 1.51$ (Set 1) $1.46 \le M \le 1.59$ (Set 2)
Case IV: 11/6	$0.92 \le M \le 0.98$	Case IX: 1/16	$1.37 \le M \le 1.6$
Case V: 9/8	$0.96 \le M \le 1.04$		

III. THE MPS-SPWM TECHNIQUE

The MPS-SPWM technique has been used in many applications in order to increase the bandwidth of the system [20]-[21]. The harmonics are controlled through the separate SPWM systems but due to the phase-shift effect between the various modulators the overall harmonic spectrum is further improved as the number of carrier waveforms is increased [23].

In this paper, the MPS-SPWM technique with four carrier waveforms is considered. This way a five-level (line-to-neutral) PWM voltage waveform is generated so that to accommodate its comparison with the MSHE-PWM technique, presented in Section II. The carrier frequency is chosen to be 9p.u. Fig. 5 presents this technique. Specifically, Fig. 5(a) shows the reference signal (sinusoidal) with the four triangular signals with each having the same frequency (9p.u.). Each carrier is phase-shifted by ¼ of its period. This ensures that the line-to-neutral voltage waveform generated and shown in Fig. 5(b) has an increased bandwidth which is equal to four times the per unit frequency. This is the result of the phase-shift introduced which allows the cancellation of the switching frequency harmonics and the associated sidebands. Closer observation of the line-to-neutral waveform reveals that the switching transitions of the waveform are for the modulation index shown 7 and 11 respectively. This of course varies according to the modulation index.

When looking at the spectrum, as the theory of PWM suggests, the first significant harmonics will be centered around the 4x9=36p.u. frequency. For the 50-Hz system shown in Fig. 5, the first point of interest in the spectrum becomes the 36p.u. frequency which is 1800-Hz frequency. The sidebands are also present and these include harmonics of 34p.u., 32p.u., 30p.u. and 28p.u. This implies that the most significant sideband harmonic eliminated due to the PWM switching is the 28p.u. or 1400-Hz. This is shown in Fig. 5(c).

IV. DISCUSSION OF RESULTS

In this paper, the two techniques have been compared in order to identify any potential benefits from using the

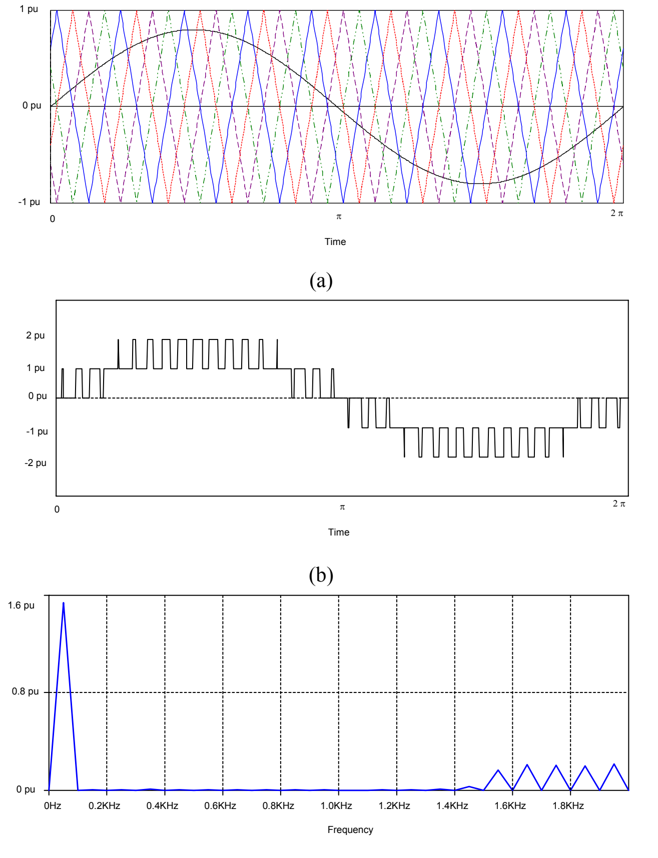

Fig. 5: Multicarrier phase-shifted sinusoidal PWM technique for five-level line-to-neutral switching pattern using four carriers. (a) Reference and four carrier triangular signals with 9p.u. frequency. (b) Line-to-neutral switching pattern directly controlled by the comparison of the signals. (c) Spectrum of the line-to-neutral waveform showing the bandwidth being almost 4 times the 9p.u. as the theory suggests (around 36p.u. minus the sidebands).

Table 2: Comparison between the two techniques; MPS-SPWM and MSHE-PWM.

Parameter	MPS-SPWM	Proposed MSHE-PWM	Improvement
Maximum modulation	1.575 p.u.	2.04 p.u.	23%
First significant harmonic	53 p.u.	28 p.u.	89%

MSHE-PWM. The MPS-SPWM technique is obviously easier to implement as the switching transitions are directly controlled by the comparison of signals which can be easily varied to control the modulation index.

The MSHE-PWM offers a challenge from the calculation point of view since the system of equations that needs to be solved is not an easy one. However, in this paper, it is shown that when the two techniques are studied, the proposed MSHE-PWM technique offers significant benefits which can justify the extra effort involved in solving the equations. The SPWM provides switching angles that are not optimum and mathematically are not calculated in order to eliminate the maximum number of possible harmonics from the spectrum. When the mathematical approach is followed, the maximum attainable modulation index increases to 2.04 p.u. when compared with the 1.575 p.u. possible with the MPS-SPWM technique. The reason being that once overmodulation is used for the MPS-SPWM, the low-order harmonics are introduced. This was resolved in two-level PWM systems with the introduction of third harmonic into the reference signal to increase the gain before bandwidth deteriorates. In the multilevel case however, this is not possible and the most significant harmonic in the case of the MPS-SPWM is the 28p.u. frequency. With the proposed approach, the harmonic is tightly controlled for all modulation indices and the switching angles available can eliminate up to 49p.u.. The 51p.u. happens to be a multiple of three therefore the first significant harmonic becomes the 53p.u. This results in an 89% increase of the bandwidth without any further need to increase the switching transitions.

These benefits are summarized in Table 2. This confirms that the mathematical approach to harmonic control in a multilevel system is a beneficial approach although the way the angles are calculated requires effort and computing time.

V. CONCLUSION

A new five-level SHE-PWM technique has been proposed in this paper. The various angles are calculated using a minimization technique with a biased search optimization approach. This approach results in an efficient method to obtain the switching transitions when other approaches documented in the technical literature present quite a challenge. It is shown that these angles can be computed for all modulation indices by using a distribution ratio and search for solutions. When compared with the conventional multicarrier PS-SPWM technique and keeping the number of transitions the same, the proposed method offers significant benefits for increased modulation index and higher bandwidth tightly controlled throughout the entire range. Selected results have been presented to confirm the theoretical findings.

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