Selective Harmonic Mitigation Based Self-Elimination of Triplen Harmonics for Single-Phase Five-Level Inverters

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***Abstract*—In this paper, a modified selective harmonic mitigation pulse amplitude modulation (SHM-PAM) is presented to be capable of canceling all triplen harmonic orders and suitable for single-phase application of five-level type of voltage source inverters. To this end, a new constraint is established for the two switching angles (α_1, α_2) to derive the new formula for the harmonics' amplitude, which results in self-elimination of all triplen harmonics (e.g., 3rd, 9th, 15th, ...). The fifth and seventh harmonic orders are mitigated through normal operation of the proposed SHM-PAM technique. It is also shown that the proposed technique is extendable to other multilevel voltage waveforms and a flowchart of self-elimination of all triplen harmonics has been presented. Mathematical analysis supported by experimental investigations show the desired performance of the proposed SHM-PAM algorithm on a two-cell single-phase cascaded H-bridge inverter as a typical five-level configuration in dealing with linear and nonlinear loads. Then, it is demonstrated that the maximum number of harmonic orders would be controlled with the minimum number of available angles in a low switching frequency voltage waveform.**

***Index Terms*—Five-level cascaded H-bridge (CHB) inverter, multilevel inverters, power quality, selective harmonic mitigation pulse amplitude modulation (SHM-PAM) and pulsewidth modulation (PWM), self-triplen harmonic elimination.**

I. Introduction

MINIMIZATION of low-order harmonic amplitudes at low switching frequency to satisfy grid code requirements could find a way through the selective harmonic mitigation pulsewidth modulation (SHM-PWM) technique [1]–[4]. SHM has been introduced based on the optimized selective harmonic elimination (SHE) [5] method as an improvement to control more harmonic orders. SHM-PWM has proven to involve all harmonic orders below 49th; those are taken into power quality evaluation, in order to overcome SHE disadvantage of leaving noneliminated orders uncontrolled [6]–[8]. Hence, an objective function (OF) has been defined to turn SHM equations into an optimization technique.

The OF is adjusted to allocate appropriate coefficients to SHM equations in order to mitigate low-order harmonics amplitudes and control noneliminated ones. However, the number of mitigated amplitudes is equal to the number of angles in the equations.

The first attempt to augment amplitude mitigation without increasing the number of pulses was the pulsewidth and amplitude modulation (PWAM) technique [9], [10]. According to the SHM-PWAM principle, both dc voltage magnitudes of inverter and switching angles are considered as variable in traditional SHM equations [11]. Thus, there is a possibility of mitigating more harmonic orders proportional to the number of dc sources added into equations as variables. Afterward, SHM-PWAM was simplified into the pulse amplitude modulation (PAM) technique in [12] through generalizing a formulation that the fundamental output voltage component can be directly controlled via dc input voltage. Several modifications have also been conducted to improve SHM-PAM in order to deal with more harmonic orders with the same number of variables. In [13], the SHM-PAM technique was applied on strictest power quality requirements and proposed to be used in back-to-back converter applications as active front end rectifiers.

Another critical challenge is in single-phase inverters where both triplen and nontriplen harmonics must be considered in the equations due to the fact that triplen harmonics exist in single-phase systems inherently. Then, there would be more undesired low harmonic orders in single-phase equations compared to the three-phase one, which should be controlled. Furthermore, triplen harmonic orders have severer standard amplitude limitation than the nontriplen ones, which weakens the SHM flexibility. The standard limitations for triplen orders higher than 15th are below 0.2%. In fact, SHM should have the ability of eliminating triplen harmonic orders in a single-phase inverter. In [14], it was shown that extra pulses are required to keep SHM flexibility in a single-phase inverter in order to increase the chance of controlling triplen amplitudes below the determined limitations in addition to mitigate the nontriplen ones. Despite this, the number of properly minimized triplen orders was limited. Also, an optimization technique has been proposed in [15] for single-phase inverters to empower angles solving method to

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search for a solution to control maximum number of harmonic amplitudes with the same switching frequency. However, the proposed method could only minimize two more triplen harmonic amplitudes for some specific modulation index. As well, there is no analytical investigation to support the reason for extra triplen harmonic minimization.

In this paper, an improved SHM-PAM technique is presented to suppress maximum number of harmonic amplitudes in single-phase inverters using minimum possible number of angles. In fact, it is shown that all triplen harmonics would be eliminated through a proposed condition for two switching angles without adding extra pulses. For this purpose, a relation for two angles in a five-level low switching voltage waveform with equal voltage steps has been found to eliminate all triplen harmonic amplitudes, inherently. Due to equality of voltage steps, it can be concluded that the proposed scheme is applicable on all five-level inverters including diode clamped [16], flying capacitor (FC) [17], cascaded H-bridge (CHB) [18], and pack U-cell (PUC) [19], [20]. Then, the SHM-PAM equations are rewritten using the new harmonic amplitude formulation derived from two angles' condition to mitigate the fifth and seventh harmonic orders in normal variable calculations. Some mathematical analysis has been done on harmonic amplitudes and voltage THD to confirm the obtained values for switching angles and input dc voltage index as well as possibility of more nontriplen harmonic amplitude mitigation. The proposed algorithm is implemented on a single-phase five-level CHB inverter to verify its performance on eliminating and mitigating specified harmonic orders under both linear/nonlinear loads. Section II includes conventional SHM-PWM and PAM equations for low switching frequency five-level CHB inverters. The modified SHM-PAM equations with self-elimination of all triplen harmonic orders by applying a new two angles' condition are presented in Section III. Moreover, a general solution for self-elimination of all triplen orders in waveforms with arbitrary number of levels is formulated and described at the end of Section III. The achieved results for two angles and dc voltage are confirmed through analyzing the harmonic amplitudes and voltage THD in Section IV. Experimental results are compared with simulation and theoretical ones and discussed in Section V. Section VI concludes this paper.

II. Conventional Single-Phase SHM-PAM Technique

A. Five-Level Inverter and Associated Waveform

Fig. 1 shows a single-phase two-cell CHB inverter topology, which generates a five-level voltage waveform. Each cell is connected to an independent dc voltage source. These two sources can have same or different voltage amplitudes to produce equal or unequal output voltage levels. Fig. 2 depicts a five-level low switching frequency voltage waveform with two switching angles in the first quarter cycle. As it is evident, low switching five-level waveform can provide the minimum number of switching angles' equations among all multilevel waveforms. In general, there are two types of multilevel voltage waveforms including low and high switching frequency. Although the number of angles is arbitrarily selected for each voltage level in high switching waveform, it is confined by levels in low switching one, as shown in Fig. 2.

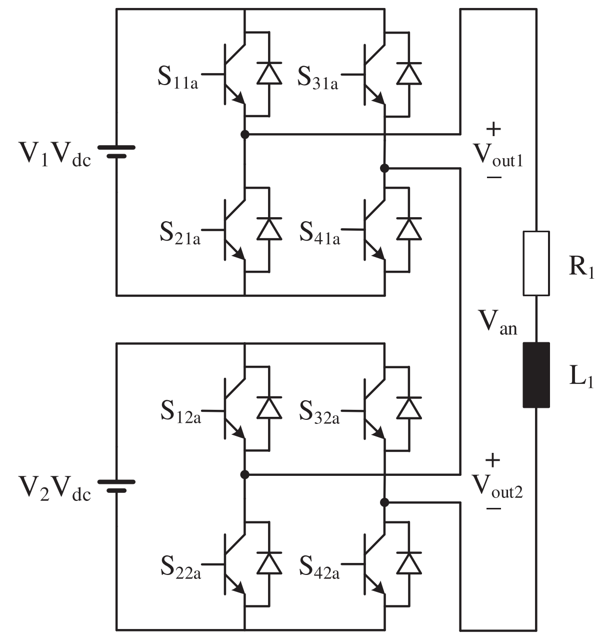


Fig. 1. Single-phase five-level CHB inverter topology.

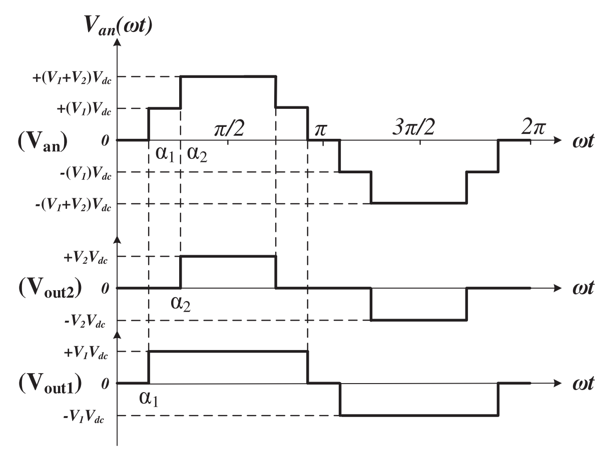


Fig. 2. Five-level low switching frequency voltage waveform.

B. Single-Phase SHM-PAM Principle

The Fourier series decomposition of voltage waveform, with the quarter wave symmetry, includes only odd coefficients and can be expressed as follows:

$$V_{\text{out}} = \sum_{n=1,3,5,\ldots}^{\infty} (H_n \sin(n\omega t)). \tag{1}$$

Where H_n are the odd Fourier series coefficients and represent the nth harmonic order amplitude. Using the five-level low switching frequency voltage waveform shown in Fig. 2, H_n can be computed as follows:

$$\begin{cases} H_n = \frac{4}{n\pi}\left(V_1 \cos\left(n\alpha_1\right) + V_2 \cos\left(n\alpha_2\right)\right) \\ \forall n = 1, 3, 5, \ldots \end{cases} \tag{2}$$

TABLE I
NONTRIPLEN AND TRIPLEN HARMONICS AMPLITUDES STANDARD

Nontriplen orders		Triplen orders	
Harmonic order (n)	Maximum allowable level (L_n)	Harmonic order (n)	Maximum allowable level (L_n)
5	6%	3	5%
7	5%	9	1.5%
11	3.5%	15	0.5%
13	3%	21	0.5%
17	2%	>21	0.2%
19	1.5%		
23	1.5%		
25	1.5%		
>25	0.2 + 32.5/n		

Noticing (2), H_n is computed with respect to the two parameter values: switching angles and dc voltages indices. In the SHM-PWM technique, only switching angles must be calculated and the dc voltage indices are presumed as 1 p.u. So, there would be two available variables including two switching angles (α_1, α_2 and $V_1 = V_2 = 1$ p.u.) in Fig. 2, which means that only one harmonic amplitude can be precisely controlled. However, in the SHM-PAM technique, dc voltage indices can be considered as variables in order to increase the chance of harmonic mitigation. Therefore, the number of variables is increased to four; two switching angles as well as two dc voltage indices (α_1, α_2 and V_1, V_2). Since SHM-PAM provides more variables, it has more flexibility than SHM-PWM in a five-level low switching frequency voltage waveform where the number of pulses is limited. Moreover, the prominent feature of SHM-PAM technique is to decrease the calculation volume in terms of iteration. When the SHM-PWM equations need to be computed for each value of m_a in a specific range, the PAM relations are calculated once to cover same range of m_a. This will also hugely decrease the required memory capacity in a microcontroller for implementing the PAM technique since look up table is not required any more.

The principle of PAM is on the idea that the amplitude of staircase output voltage changes whereas the pulsewidths are kept constant for different modulation indices. For this purpose, the dc voltage indices have to change proportionally with respect to the modulation index (m_a) as follows:

$$\begin{cases} V_1 = A_1 \cdot m_a \\ V_2 = A_2 \cdot m_a \end{cases} \tag{3}$$

where A_1 and A_2 are linear ratios between dc voltage indices and modulation index.

Regarding the SHM technique, the fundamental amplitude has to be set equal to modulation index to produce desired fundamental voltage. Moreover, the undesirable harmonic amplitudes must be mitigated below determined levels, as given in Table I. The determined levels ascertain maximum allowable magnitude for each harmonic order. The maximum harmonic amplitudes categorized in [21] and [22] and listed in Table I are used as the reference in this paper. Since both triplen and nontriplen harmonic orders below 49th are important in single-phase systems, the single-phase SHM equations include harmonic orders from 3rd to 49th. Considering (3) into the harmonic amplitude formula (2), the conventional single-phase SHM-PAM equations for the five-level low switching frequency voltage waveform of Fig. 2 are written as the following:

$$\begin{cases} E_1 = \frac{4}{\pi}(A_1 \cos(\alpha_1) + A_2 \cos(\alpha_2)) = 1 \\ E_n = \frac{4}{n\pi}(A_1 \cos(n\alpha_1) + A_2 \cos(n\alpha_2)) \leq L_n \\ \forall\, n = 3, 5, \ldots, 49 \\ 0 < \alpha_1 < \alpha_2 < \frac{\pi}{2} \text{ and } 0 < A_{1,2} < 1. \end{cases} \tag{4}$$

According to (4), the number of equations exceeds the number of pulses, which reduces the chance of harmonic mitigation. In order to get a solution, due to the complexity and high nonlinearity of (4), the set of equations is expressed as a unidimensional function, so-called OF of the problem. In this way, the problem has become a multivariable single function optimization problem that can be solved with several heuristic methods as particle swarm optimization, artificial bee colony algorithm, simulated annealing, Tabu search, etc. [23], [24].

Equation (5) shows a possible OF for the problem described by (4). It can be seen that every equation has been turned into a quadratic error term multiplied by a weighting coefficient. These weighting coefficients achieve to prioritize some terms versus others. With this formulation, other terms or figures of merit can be easily included like the THD

$$\text{OF}(\alpha_1, \alpha_2 \text{ and } A_1, A_2) = C_1(E_1 - m_a)^2 + \left(\sum_{n=3,5,\ldots 49} C_n(E_n - m_a L_n)^2\right) + C_{\text{THD}}\text{THD}. \tag{5}$$

As mentioned above, each harmonic order contributes with a weighted term on the OF. On one hand, the primary objective is to get desired fundamental harmonic amplitude, so C_1 must be much higher than any others'. On the other hand, it is preferred to mitigate low-order harmonics and consequently their weighting coefficients should be greater. As the formulated problem is considering four variables (two angles and two dc sources amplitudes), it is logical to assume that there will be at least a solution that achieves to fix the desired modulation index and conveniently mitigate the three first harmonic orders (third, fifth, and seventh). Also, if THD is considered in the OF, C_{THD} must be less than the seventh harmonic order but greater than ninth since there is no guarantee for more harmonic mitigation. However, assuming C_{THD} greater than C_9 gives more control on remaining higher harmonic orders. Equation (6) shows the harmonic orders and THD coefficient modeling.

$$C_1 >> C_3 > C_5 > C_7 >> C_{\text{THD}} > C_9 > \cdots > C_{49}. \tag{6}$$

III. SELF-ELIMINATION OF ALL TRIPLEN HARMONICS

A. *Proposed Condition for Two Switching Angles (α_1 and α_2)*

In the conventional single-phase SHM-PAM, triplen harmonics are considered beside nontriplen ones, which increases the number of equations in OF. The main issue is the limitation of available variables in the five-level low switching frequency voltage waveform. Although there are four variables in SHM-PAM equations (4), it is not ensured that more than three harmonic orders including third, fifth, and seventh would be properly mitigated. In this paper, a new condition for switching angles of Fig. 2 has been presented to control maximum number of harmonics with minimum number of variables. It will be proven that the new design criteria inherently results in full cancelation of all triplen harmonics and single-phase SHM-PAM equations could be written as three-phase ones excluding triplen harmonics.

Triplen harmonics are multiple of third orders and have mathematical sequence. Hence, all the triplen harmonics can be removed if one of them is eliminated for a specific condition of angles. Therefore, the first triplen harmonic amplitude must be set to zero to obtain the condition for angles.

$$H_3 = \frac{4}{3\pi}\left(V_1\cos(3\alpha_1) + V_2\cos(3\alpha_2)\right) = 0. \tag{7}$$

The voltage levels should be identical to find a solution for (7) that yields a simplified relation between two switching angles as (8). The voltage levels equality means that the proposed switching technique can also be implemented on all single-dc-source five-level inverters, such as FC and PUC. Then, assuming equal steps in Fig. 2, ($V_1 = V_2 = V$ and $A_1 = A_2 = A$, then $V = A \cdot m_a$), the condition for two angles will be found by solving the following equation:

$$\cos(3\alpha_1) + \cos(3\alpha_2) = 0. \tag{8}$$

The general solution for trigonometric equation of $\cos(x) = \cos(y)$ is $x = 2K\pi \pm (\pi - \mathrm{y})$. Considering this fact, (9) is achieved from (8)

$$\alpha_2 = \frac{(2K \pm 1)\pi}{3} \pm \alpha_1. \tag{9}$$

K belongs to the set of integers which is $Z = 0, \pm 1, \pm 2, \ldots$, but the possible relation between two switching angles is attained only for $K = 0$. For other values of *K*, the obtained relations are out of the valid range for switching angles, which is between 0 and $\pi/2$. In other words, they are in contrast to the main switching angles' condition of $0 < \alpha_1 < \alpha_2 < \pi/2$. Therefore, the following conditions are finally obtained for two angles (α_1 and α_2) when $K = 0$:

$$\begin{cases} (a): \alpha_2 = \frac{\pi}{3} - \alpha_1 \\ (b): \alpha_2 = \frac{\pi}{3} + \alpha_1. \end{cases} \tag{10}$$

These two obtained angles' conditions can be also examined through applying (10) on main angle condition ($0 < \alpha_1 < \alpha_2 < \pi/2$) to designate a valid range for the first switching angle (α_1). In this case, the valid range for α_1 is obtained for both conditions similarly as follows:

$$0 < \alpha_1 < \frac{\pi}{6}. \tag{11}$$

In order to find which condition must be used for writing single-phase SHM equations, the first new harmonic amplitude formulation is attained for both conditions. The new H_n with equal voltage level can be written as (12) by separately substituting these two conditions into (2)

$$\begin{cases} (a): H_n = \frac{8V}{n\pi}\left(\cos\left(n\frac{\pi}{6}\right)\cdot\cos\left(n(\alpha_1 - \frac{\pi}{6})\right)\right) \\ (b): H_n = \frac{8V}{n\pi}\left(\cos\left(n\frac{\pi}{6}\right)\cdot\cos\left(n(\alpha_1 + \frac{\pi}{6})\right)\right). \end{cases} \tag{12}$$

Since in the SHM technique, the first triplen harmonic amplitude must be equal to m_a and $V = A \cdot m_a$, so the valid range of each fundamental harmonic amplitude presented in (12) is obtained when it is supposed that $0 < \alpha_1 < \pi/6$

$$\begin{cases} (a): \frac{\sqrt{3}}{2} < \cos\left(\alpha_1 - \frac{\pi}{6}\right) < 1 \\ (b): \frac{\sqrt{3}}{2} < \cos\left(\alpha_1 + \frac{\pi}{6}\right) < \frac{1}{2}. \end{cases} \tag{13}$$

As it can be seen from (13), the second harmonic amplitude formulation derived from the second switching angle condition does not have a valid range for the first harmonic amplitude and cannot be used for writing associated single-phase SHM equations. Consequently, the first harmonic amplitude related to the first condition ($\alpha_2 = \pi/3 - \alpha_1$) is considered to define new single-phase SHM equations with ability of self-elimination of all triplen harmonic orders as follows:

$$\begin{cases} E_1^{\mathrm{new}} = \frac{8A}{\pi}\cdot\cos\left(\frac{\pi}{6}\right)\cdot\cos\left((\alpha_1 - \frac{\pi}{6})\right) = 1 \\ E_n^{\mathrm{new}} = \frac{8A}{n\pi}\cdot\cos\left(n\frac{\pi}{6}\right)\cdot\cos\left(n(\alpha_1 - \frac{\pi}{6})\right) \le L_n \\ \forall n = 5, 7, \ldots, 49 \text{ and } 0 < \alpha_1 < \frac{\pi}{6} \\ 0 < \alpha_1 < \frac{\pi}{6} \text{ and } 0 < A < 1. \end{cases} \tag{14}$$

According to (14), the triplen harmonic orders, as it has already been supposed, have zero amplitude owing to the term $\cos(n\pi/6)$. Hence, it is not required to involve them into the equations, so the number of equations is lower than that of the conventional single-phase SHM-PAM provided in (4). The way of solving switching angle (α_1) and the voltage relation (*A*) from (14) is exactly as described for (4). Once (14) is turned into the unidimensional OF in (15), the weighting coefficients can be modeled in an identical manner summarized in (6), resulting for the proposed modified SHM-PAM, as indicated in (16). Also, imposing SHM equations to be solved in the specified angles' range ($0 < \alpha_1 < \pi/6$) makes optimization algorithm act faster to find the angles' value since it is searching in smaller range compared to the conventional SHM-PAM that it must search in the range 0 to $\pi/2$

$$\mathrm{OF}(\alpha_1 \text{ and } A) = C_1^{\mathrm{new}}\left(E_1^{\mathrm{new}} - m_a\right)^2 + \left(\sum_{n=5,7,\ldots 49} C_n^{\mathrm{new}}\left(E_n^{\mathrm{new}} - m_a L_n\right)^2\right) + C_{\mathrm{THD}}^{\mathrm{new}}\mathrm{THD} \tag{15}$$

$$C_1^{\mathrm{new}} >> C_5^{\mathrm{new}} > C_7^{\mathrm{new}} >> C_{\mathrm{THD}}^{\mathrm{new}} > C_{11}^{\mathrm{new}} > \cdots > C_{49}^{\mathrm{new}}. \tag{16}$$

The remaining angle (α_2) can be derived from α_1 using the first formula of (10) ($\alpha_2 = \pi/3 - \alpha_1$). As well, the existence of three variables (α_1, α_2, and *A*) gives the mitigation of two harmonic orders (fifth and seventh). The calculated switching angles and parameter *A* have been shown in Table II. The voltage

TABLE II
COMPUTED VALUES FOR SWITCHING ANGLES (RADIAN) AND PARAMETER A

α_1	α_2	A
0.2581	0.7891	0.470

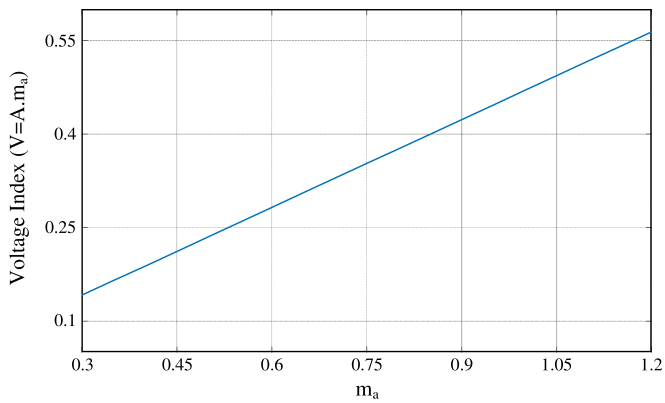


Fig. 3. Voltage index of separated dc sources in a single-phase five-level CHB inverter.

index for each separated dc source in a single-phase five-level CHB inverter (V) is obtained based on $V = A \cdot m_a$. Fig. 3 shows the voltage index versus modulation index. Also, the proposed procedure of self-elimination of all triplen harmonic amplitudes has been demonstrated as a flowchart in Fig. 4.

B. General Solution for Self-Elimination of Triplen Orders in Other Multilevel Voltage Waveforms

Although the proposed technique has been applied on a five-level low switching frequency voltage waveform to deal with maximum number of amplitudes while the minimum number of transitions is available, it can be extended to other types of multilevel voltage waveforms. As it has been illustrated in (10), a specified relation between two angles has been found to eliminate the first triplen harmonic order and all other triplen orders as the result. Accordingly, the same procedure can be used for other multilevel voltage waveforms to eliminate all triplen harmonic orders. The general format of the first triplen harmonic amplitude for a K-level multilevel voltage waveform can be expressed as follows:

$$H_3 = \frac{4}{3\pi}\sum_{i=1}^{k}\begin{bmatrix} V_1 \sum_{j=1}^{m_1} (\pm\cos(3\alpha_j)) \\ +V_2 \sum_{j=m_2}^{m_3} (\pm\cos(3\alpha_j)) \cdots \\ +V_i \sum_{j=m_{n-1}}^{m_n} (\pm\cos(3\alpha_j)) \end{bmatrix}. \quad (17)$$

m_n is the number of angles in each level. The sign of cosine functions depends on how switching angles are distributed among voltage levels and is precisely determined using Fourier series analysis. Then, the first triplen amplitude can be equivalent to zero if the trigonometric terms for each voltage level in (17) are set to zero as presented in (18). Therefore, the conditions among switching angles will be attained by solving the

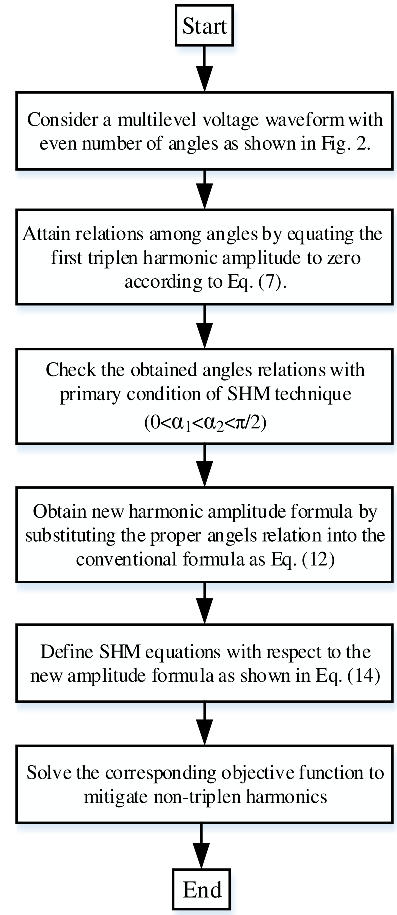


Fig. 4. Flowchart of the proposed procedure for elimination of all triplen harmonics.

following equations:

$$\begin{cases} \sum_{j=1}^{m_1} (\pm\cos(3\alpha_j)) = 0 \\ \sum_{j=m_2}^{m_3} (\pm\cos(3\alpha_j)) = 0 \\ . \\ . \\ . \\ \pm \sum_{j=m_{n-1}}^{m_n} (\pm\cos(3\alpha_j)) = 0. \end{cases} \quad (18)$$

The corresponding single-phase SHM equations will be achieved from a new harmonic amplitude formula considering the obtained conditions for switching angles.

C. Comparative Study Between the Conventional SHM-PWM/PAM and Modified SHM-PAM Techniques

Table III shows the number of variables, the number of harmonic orders that have chance to be controlled, and the number of equations in the conventional single-phase SHM-PWM/PAM and modified single-phase SHM-PAM techniques in a five-level low switching frequency voltage waveform. In the conventional single-phase SHM-PWM technique for the low switching five-level waveform, there are two switching angles, so just third harmonic is controlled; but, it can be applied on any five-level inverter since it is independent of dc sources. The conventional

TABLE III
COMPARISON BETWEEN THE CONVENTIONAL SHM-PWM/PAM AND THE MODIFIED SHM-PAM

	Conventional SHM-PWM	Conventional SHM-PAM	Modified SHM-PAM
Number of variables (switching angles and dc sources)	2	4	3
Number of controlled harmonics in the range of 3rd–49th	1	3	10
Required inverter's type	Any five-level inverter	Five-level CHB inverter	Any five-level inverter
Number of single-phase SHM equations	25	25	17

single-phase SHM-PAM has four variables (two switching angles and two dc source) in a five-level CHB that can control three harmonic orders including third, fifth, and seventh. However, it is limited to a five-level CHB inverter topology where there are enough dc sources to be used as variables in SHM equations.

The modified single-phase SHM-PAM technique as the proposed method for self-elimination of triplen harmonics can control 10 harmonic orders in the range 3rd–49th while only three variables (two angles and one dc source) have been considered. Moreover, since the dc sources are assumed equal, it can be applied on any five-level inverter topology. It must be mentioned that all triplen harmonics are eliminated in the modified SHM-PAM technique due to obtained angles' constraint. Therefore, the modified SHM-PAM technique not only controls more harmonic orders, but also it is not limited to a particular inverter topology.

In addition to the aforementioned points, the conventional single-phase SHM-PWM and PAM have 25 equations since they should consider both triplen and nontriplen harmonic orders. On the contrary, the modified single-phase SHM-PAM has only 17 equations since all triplen harmonics are naturally eliminated due to the obtained angles' constraint of (10). Therefore, single-phase modified SHM-PAM equations have less complexity to be solved even with less number of variables.

IV. Mathematical Analysis of Proposed Condition for Two Switching Angles

A. Harmonic Amplitudes

The Fourier series has been presented based on the conception that every periodic function can be defined by sum of sine and cosine functions. Since harmonic amplitude has been defined by two variables in (12), it is possible to show the harmonics amplitude waveform to investigate the harmonics amplitudes mitigation capacity.

To this end, the amplitudes of harmonics orders (H_1, H_5, H_7, and H_{11}) considering SHM-PAM equations (14) have been outlined in three-dimensional (3-D) space based on two variables (A, α_1). The first equation containing the first harmonic amplitude has been separately plotted in Fig. 5 to determine the range of parameter A. As it is shown in *X–Z* (*A-Magnitude*) view, two

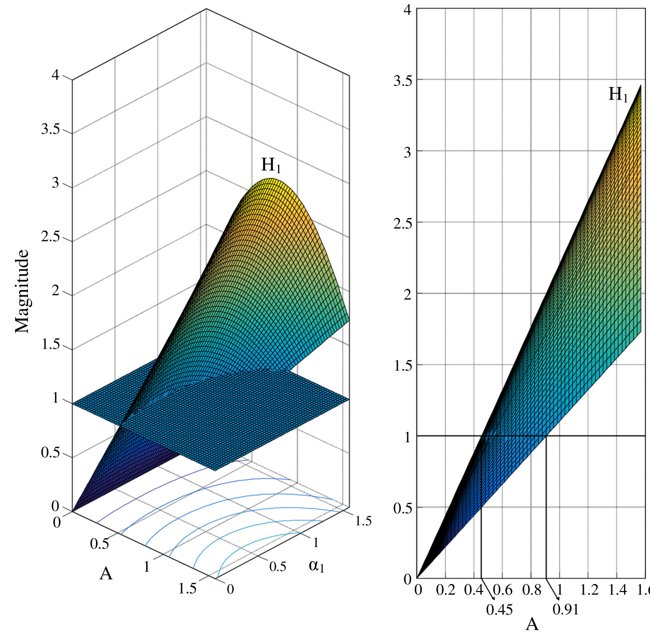


Fig. 5. 3-D waveform of the first harmonic (H_1).

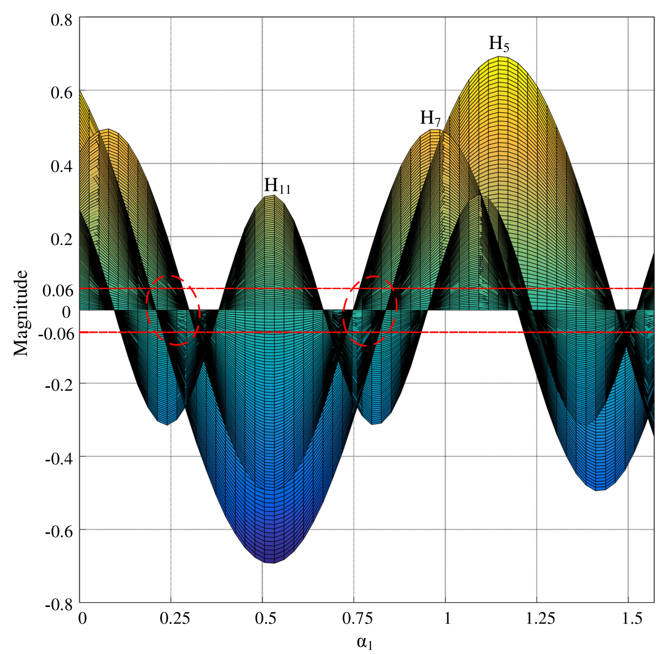


Fig. 6. 3-D waveform of harmonic orders H_5, H_7, and H_{11}.

figures have intersected when $0.45 < A < 0.91$, which means the first harmonic has the possibility of having the exact value in (14). 3-D waveform of three harmonic amplitudes (H_5, H_7, and H_{11}) has been drawn in Fig. 6 to find accurate values of A and α_1 as well as to investigate if more harmonic orders can be mitigated. To prevent complexity in analysis, 3-D waveform of harmonic orders has been shown in *Y–Z* (α_1-*Magnitude*) view in Fig. 6.

The horizontal dotted lines in Fig. 6 determine the standard value for fifth harmonic order, which has the highest maximum allowable value among all harmonic orders. Two areas have also

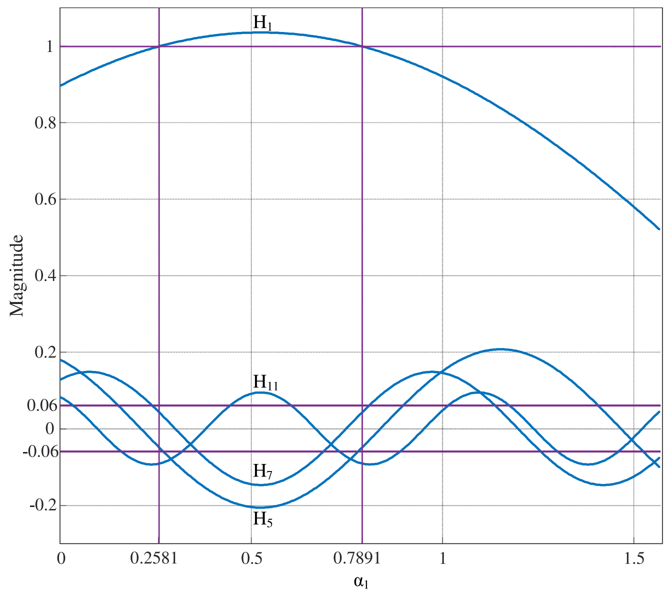


Fig. 7. Sine waveform of harmonics amplitudes: H_1, H_5, H_7, and H_{11}.

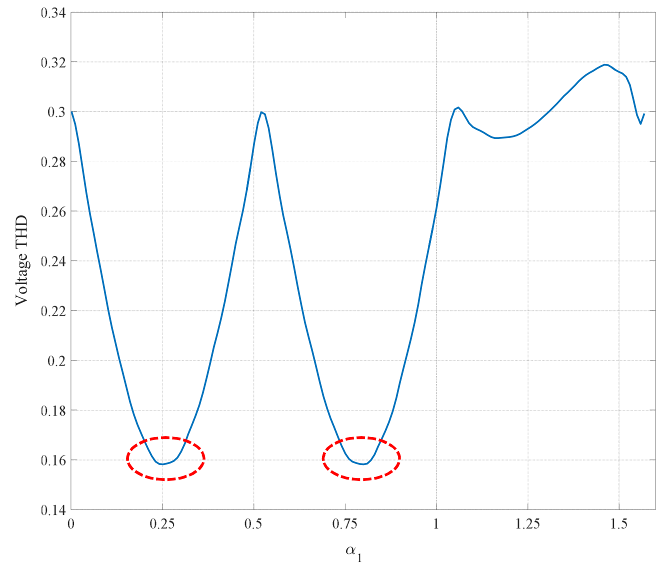


Fig. 8. Voltage THD curve based on switching angle (α_1).

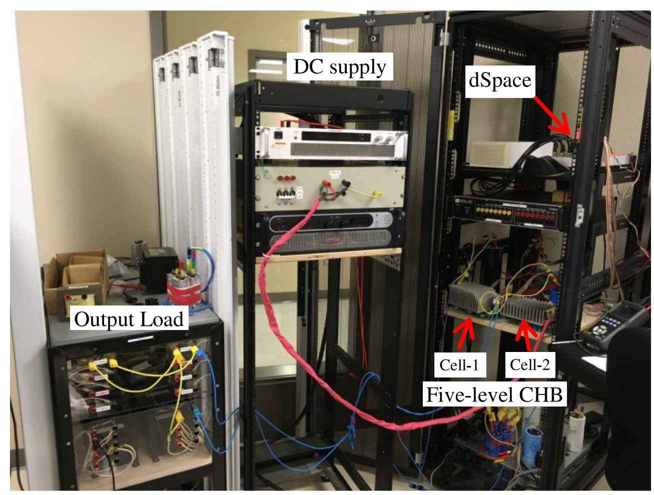


Fig. 9. Experimental test setup of a five-level CHB inverter.

been specified by dashed ovals in which the fifth and seventh harmonic orders have chance to meet the grid codes. By analyzing 3-D waveform of mentioned harmonic orders for various values of parameter A, it has been found out that fifth and seventh orders have admissible amplitude for $A = 0.470$.

Fig. 7 shows the amplitude of harmonic orders H_1, H_5, H_7, and H_{11} versus α_1 when $A = 0.470$. As illustrated in that figure, the first harmonic amplitude has the exact magnitude (1) in two points, which is regarding with two values in degree axis. These values represent the obtained switching angles (α_1 and α_2) shown in Table II. Therefore, the specific values of obtained switching angles have been validated by Fig. 7 visualization.

B. Voltage THD

Moreover, it is possible to obtain the THD graph with respect to the switching angles in the proposed single-phase SHM technique. It can be used to determine the range of switching angles value while THD has a minimum value. THD is the figure of merit for quality evaluation of voltage or current waveform and is defined as follows:

$$\mathrm{THD} = \frac{\sqrt{\sum_{n=3,5,7,\ldots} H_n^2}}{H_1}. \tag{19}$$

The voltage THD formula for the proposed switching technique with self-elimination of triplen harmonics is achieved by substituting new equation of harmonic amplitudes [the first formula of (12)] into (19) as

$$\mathrm{THD} = \frac{\sqrt{\sum_{n=5,7,11,\ldots} \frac{\left(\cos\left(n\frac{\pi}{6}\right).\cos\left(n\left(\alpha_1-\frac{\pi}{6}\right)\right)\right)}{n}}}{\left(\cos\left(\frac{\pi}{6}\right).\cos\left(n\left(\alpha_1-\frac{\pi}{6}\right)\right)\right)}. \tag{20}$$

Since voltage THD formula of (20) is written based on only one switching angle (α_1), it would be also possible to depict the THD waveform with respect to the angle in order to find the minimum THD value. Fig. 8 shows voltage THD versus the first switching angle (α_1). According to Fig. 8, THD has two minimum points (shown by dashed circles), which are complying with two obtained switching angles' values (α_1 and α_2) listed in Table II. It assures that the obtained angles have the optimum values and consequently lead to have minimum voltage THD.

V. Results Discussion

The harmonic contents of both the conventional and improved single-phase SHM-PAM techniques are compared to confirm that the proposed single-phase SHM-PAM technique results in better harmonic content. Afterward, the proposed SHM-PAM technique is implemented on a single-phase five-level CHB inverter prototype built in the laboratory using dSpace as real-time controller and evaluated under both linear and nonlinear loads. Fig. 9 shows the corresponding experimental test setup. The nominal dc source (V_{dc}) applied on each full-bridge inverter and output voltage frequency is 200 V and 50 Hz, respectively.

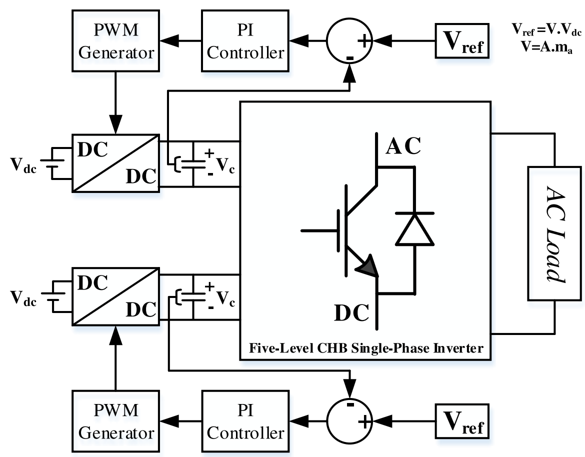


Fig. 10. Closed-loop controller for implementation of PAM.

The PAM can also be done through a dc–dc converter with closed-loop system provided by a PI controller to produce the desired dc input voltage for a CHB inverter, as illustrated in Fig. 10. Since the fundamental harmonic amplitude of the output ac voltage is determined based on m_a and the input dc voltage linearly varies with respect to m_a in the PAM technique, the output ac voltage is controlled if the input dc voltage is desirably regulated. Then, controlling of the output ac voltage can be done through adjusting m_a to produce the desired input dc voltage, as shown in closed-loop controller of Fig. 10.

A. Analytical Comparison of Harmonic Amplitudes

The conventional single-phase SHM-PAM with four variables (α_1, α_2, and V_1, V_2) in low switching frequency five-level leads to mitigation of three harmonics including third, fifth, seventh, and the first unmitigated order is ninth presented in [9]. On the other hand, it is shown that the improved single-phase SHM-PAM with proposed angles' condition eliminates all triplen harmonics in addition to mitigate harmonic amplitudes fifth, seventh, and the first unmitigated harmonic amplitude is 11th. Then, more harmonic amplitudes have been reduced with less number of variables. Fig. 11 illustrates a comparison among harmonic amplitudes of the conventional and improved single-phase SHM-PAM with standard level in range 3rd–49th. Fig. 11(a) shows nontriplen amplitudes as well as THD and Fig. 11(b) includes triplen ones. According to Fig. 11(a), two nontriplen harmonic orders fifth and seventh have been mitigated properly in both techniques. For higher nontriplen orders, there are no remarkable differences between two techniques; the conventional SHM has lower amplitude for some orders, whereas the improved technique has better results for some others. However, lower voltage THD in the improved single-phase SHM-PAM (15.8) is mainly due to the cancelation of all triplen harmonic amplitudes, demonstrated in Fig. 11(b). Such acquired value for voltage THD is acceptable while the minimum number of angles is selected to decrease switching frequency to 100 Hz. Moreover, the remaining uncontrolled harmonics can be removed using an *LC* filter. Since the *LC* filter for the modified single-phase SHM-PAM must be tuned to 11th, it has smaller size compared with the conventional one that should be adjusted to 9th.

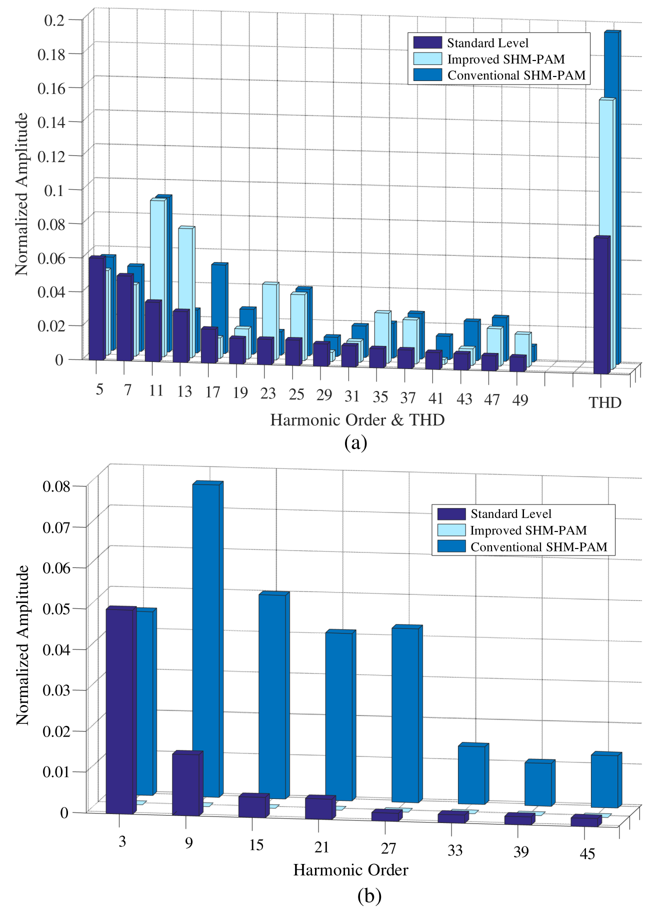


Fig. 11. (a) Nontriplen and (b) triplen amplitudes in both the conventional and improved single-phase SHM-PAM techniques.

B. Experimental Evaluation of Single-Phase CHB Performance Under Linear/Nonlinear Loads

Fig. 12 depicts the five-level voltage and load current waveforms for the modulation indices 0.45, 0.85, and 1.1. The single-phase CHB inverter is supplying linear *R–L* load that $R = 40\,\Omega$ and $L = 20\,\text{mH}$. As can be seen from voltage waveform, the width of the pulses is kept constant while modulation index changes. On the contrary, pulse amplitudes of the output voltage change linearly with respect to modulation index. As a result of invariable pulses' width of output voltage waveform, voltage THD will have a constant value as well.

Moreover, the harmonic amplitudes and voltage THD achieved from experimental result of Fig. 12 related to modulation index 0.85 have been compared to the corresponding theoretical and simulation ones. In this case, Fig. 13(a) includes nontriplen harmonic orders, whereas triplen ones are shown in Fig. 13(b). Since it was proven that triplen harmonic amplitudes are theoretically zero, Fig. 13(b) contains only simulation and experimental results of triplen amplitudes. Also, the harmonic amplitudes have been normalized by the first harmonic amplitude. The harmonic contents of these three situations

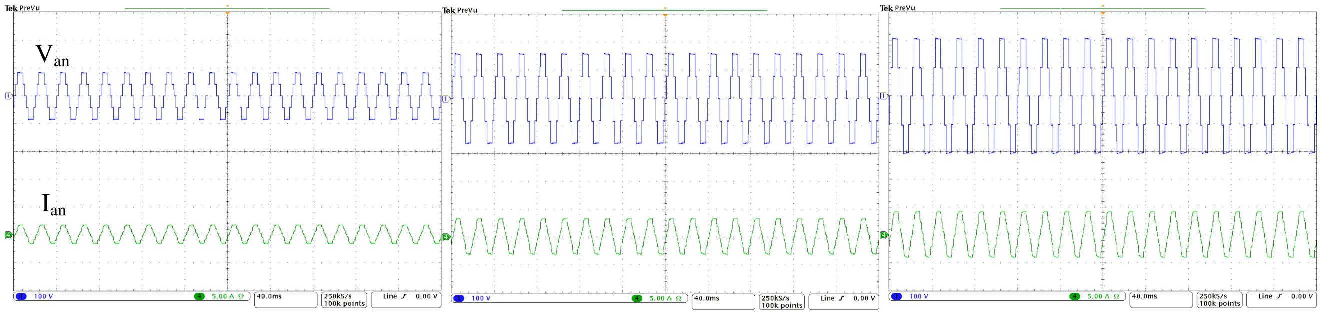
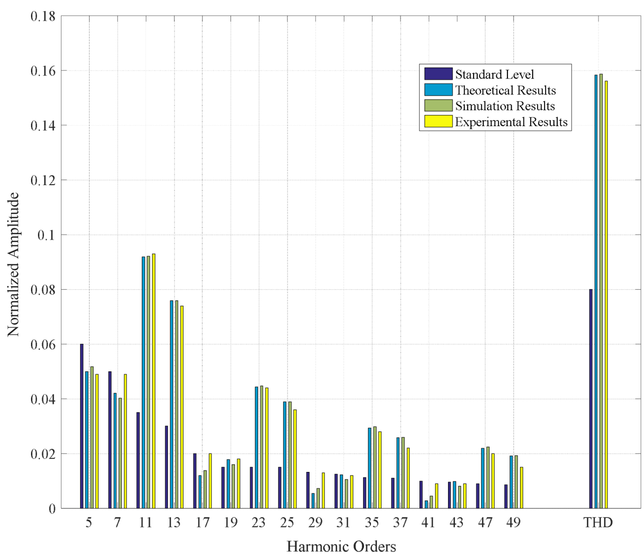
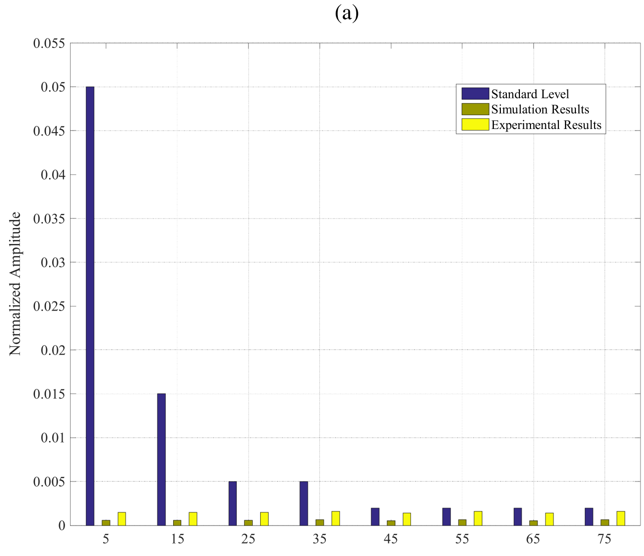


Fig. 12. Output voltage and current waveforms of a five-level single-phase CHB inverter under linear *R–L* load for different modulation indices. (a) $m_a = 0.45$, (b) $m_a = 0.85$. (c) $m_a = 1.1$.



(a)



(b)

Fig. 13. Harmonic amplitudes and voltage THD for theoretical, simulation, and experimental results. (a) Triplen orders. (b) Nontriplen orders.

(theoretical, simulation, and experimental) validate that the amplitudes of the fifth and seventh harmonic orders have been mitigated below standard level along with self-elimination of all triplen harmonics, even though, there is a negligible difference among them. The ignorable difference means while triplen harmonics theoretically are zero, they have amplitude less than 0.001 in simulation and experimental results, which is approximately zero.

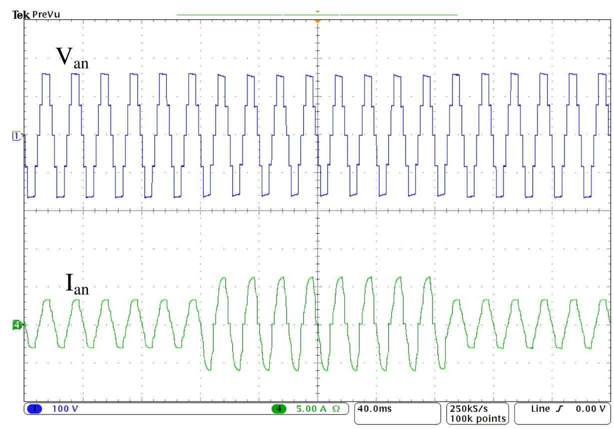


Fig. 14. Voltage and current waveforms when a five-level CHB inverter supplies both linear and harmonic loads.

Furthermore, the elimination of all triplen harmonic orders enables a CHB inverter to deal with nonlinear loads besides linear ones. A single-phase diode rectifier connected to *R–L* load has been assumed as a nonlinear load. The output rectifier load is *R–L* that $R = 40\,\Omega$ and $L = 50\,\text{mH}$. Fig. 14 demonstrates the output voltage and load current waveforms when a five-level CHB inverter supplies both linear and nonlinear loads. According to Fig. 14, there is no voltage or current transient when the diode rectifier is connected/disconnected to/from a single-phase CHB inverter. Thus, the ability of handling linear/nonlinear loads because of controlling important nontriplen low orders besides all-triplen harmonics makes the proposed switching method suitable candidate for standalone single-phase uninterruptible power supply (UPS) applications, which deals with both normal and harmonic loads in practical situations.

Moreover, in a three-phase UPS, the single-phase loads are usually fed through the fourth wire, which deals with those triplen harmonics inherently [25], [26]. Since all triplen harmonics are eliminated in the proposed method, it can also be employed in three-phase four-wire inverters for three-phase UPS applications where triplen harmonics must be suppressed to keep phase voltages balanced under linear/nonlinear and single-/three-phase loads. Considering the fact that the proposed technique is suitable for all type of five-level inverters, it can be applied on single-dc-source inverter such as NPC in case of three-phase four-wire system to use less dc sources. Furthermore, the proposed technique can be investigated for drive application where an electrical motor is supplied by back-to-back (ac–dc–ac) converters. In this regard, a PAM converter has already been introduced in [27] and [28] for drive application where the proposed SHM-PAM is a compatible technique to be applied in addition to that it removes all triplen harmonics that are harmful for electrical motors.

VI. Conclusion

In this paper, a new condition for two angles in a five-level low switching frequency voltage waveform has been proposed to modify the conventional SHM-PAM equations in order to eliminate all triplen harmonics. The fifth and seventh harmonic orders have also been mitigated through solving normal SHM relations without considering extra pulses. Therefore, it has the advantage of controlling maximum number of harmonic amplitudes with minimum number of variables in a single-phase inverter where both triplen and nontriplen orders have to be considered in the equations. Due to elimination of all triplen harmonics, the modified SHM-PAM technique has been simplified in such way that it has fewer number of equations compared to the conventional SHM-PAM technique while more harmonics could be controlled. The proposed technique has been applied on a single-phase five-level CHB inverter and tested under both linear and nonlinear loads and consequently will be a suitable candidate for a single-phase UPS application that must supply these types of loads in practical situations. On the other hand, it is also applicable in three-phase four-wire inverters where triplen harmonics must be canceled out to keep the phase voltage balanced under linear/nonlinear and single-/three-phase load conditions as well as electrical drive using PAM converters. It has demonstrated that the presented method is extendable to other multilevel voltage waveforms, and a general solution for triplen harmonics elimination has been derived. However, the details of circumstances of angle calculations must be discussed in future works to generalize a formulation of self-elimination of triplen orders and mitigation of nontriplen one appropriate for standalone inverters applications.

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