JPE 17-1-11

https://doi.org/10.6113/JPE.2017.17.1.106
ISSN(Print): 1598-2092 / ISSN(Online): 2093-4718

Non-equal DC link Voltages in a Cascaded H-Bridge with a Selective Harmonic Mitigation-PWM Technique Based on the Fundamental Switching Frequency

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Abstract

In this paper, the Selective Harmonic Mitigation-PWM (SHM-PWM) method is used in single-phase and three-phase Cascaded H-Bridge (CHB) inverters in order to fulfill different power quality standards such as EN 50160, CIGRE WG 36-05, IEC 61000-3-6 and IEC 61000-2-12. Non-equal DC link voltages are used to increase the degrees of freedom for the proposed SHM-PWM technique. In addition, it will be shown that the obtained solutions become continuous and without sudden changes. As a result, the look-up tables can be significantly reduced. The proposed three-phase modulation method can mitigate up to the 50th harmonic from the output voltage, while each switch has just one switching in a fundamental period. In other words, the switching frequency of the power switches are limited to 50 Hz, which is the lowest switching frequency that can be achieved in the multilevel converters, when the optimal selective harmonic mitigation method is employed. In single-phase mode, the proposed method can successfully mitigate harmonics up to the 50th, where the switching frequency is 150 Hz. Finally, the validity of the proposed method is verified by simulations and experiments on a 9-level CHB inverter.

Key words: Cascaded H-bridge, Multilevel converters, Particle swarm optimization, Selective harmonic mitigation PWM

I. Introduction

Nowadays, multilevel converters play an important role in the power grid applications. There are some important features of these converters that make them suitable for grid connected applications, including lower Total Harmonic Distortion (THD), lower *dv/dt*, and higher efficiency [1]-[3]. On the other hand, grid connected converters have to satisfy power quality standards [4]-[7]. In order to meet standard requirements, different modulation techniques have been presented to reduce the harmonic contents of the output voltage and current [8]-[12].

Optimal modulation techniques have been introduced to control the harmonic spectra of the output waveform and to improve the efficiency of the converter. For this reason, the Fourier series of the output waveform is extracted and optimized by one of the following main techniques.

1) Selective Harmonic Elimination-PWM (SHE-PWM).
2) Selective Harmonic Mitigation-PWM (SHM-PWM).

In SHE-PWM, the low order harmonics of the output waveform are obtained by a Fourier series and eliminated by an appropriate selection of switching angles [13]-[17]. Then the extracted switching angles are saved in look-up tables in order to be used in real-time applications. The high order harmonics are also weakened by passive filters. The main goals in the SHE-PWM method are the use of fast and effective optimization techniques to find a wide range of answers from non-linear equations [18], [19], and to find solutions for increasing the converter efficiency [9], [20]. In addition, employing a real-time SHE-PWM technique when the modulation technique does not use any look-up table saves switching angles versus modulation indices [21]. Recently, the

Manuscript received Aug. 16, 2016; accepted Oct. 17, 2016.
Recommended for publication by Associate Editor Yun Zhang.
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SHE-PWM approach has also been considered for active rectifiers in order to meet the standard requirements for the current waveforms and to balance the DC links of CHB converters [22], [33].

Recently, a new optimal modulation technique (SHM-PWM) has been introduced which tries to mitigate low order harmonics, instead of complete elimination of low order harmonics, from the output waveform [23], [24]. In this method, a higher number of harmonics can be considered compared to the SHE-PWM method. Hence, smaller and cheaper passive filters can be adopted in this method. The main goals in this method are increasing the converter efficiency by decreasing the switching frequency [25], [12], satisfying a larger number of grid codes [12], and analyzing the effect of DC link variations in the harmonic spectra [26].

Non-equal DC link voltages have been employed in some CHB converters [27]-[30], [40]. These techniques employ separate DC link voltages that are supplied by front-end converters. Non-equal DC link voltages can significantly increase the range of solution sets in optimal modulation techniques [30], [31]. More importantly, by using non-equal DC link voltages, solutions can be obtained in a continues way in the whole range of modulation indices. A comparison between employing non-equal DC link voltages in both the SHE-PWM and SHM-PWM methods with the same number of switching transitions was presented in [31].

In this paper, a modified SHM-PWM method is proposed for three-phase CHB converters with just one switching for each of the switches in a fundamental period to mitigate all of the harmonics lower than the 50th. Furthermore, the proposed SHM-PWM in single-phase converters employs a 150 Hz switching frequency for each of the switches to achieve similar results. In this paper, four power quality standards (EN 50160 [4], CIGRE WG 36-05 [5], IEC 61000-3-6 [6], and IEC 61000-2-12 [7]) are considered for the proposed SHM-PWM method. The selected grid codes in this paper are more intransigent than those in previous works [12], [17], [23], [24]. Moreover, IEC 61000-3-6 and IEC 61000-2-12 are known as international power quality standards. Thus, it is a significant advantage for modulation methods to satisfy these intransigent global standards. The contributions of this paper are:

1) The proposed SHM-PWM technique has the lowest number of switching transitions that is possible for the SHM-PWM technique. Thus, the efficiency of the proposed technique is the highest that can be achieved.

2) The proposed SHM-PWM modulation technique considers the lowest voltage harmonic limits for several standards such as (EN 50160 [4], CIGRE WG 36-05 [5], IEC 61000-3-6 [6], and IEC 61000-2-12 [7]). Thus, the solutions of the proposed technique can meet all of the power quality voltage limits.

3) The proposed SHM-PWM modulation technique is applied to both single-phase and three-phase converters.

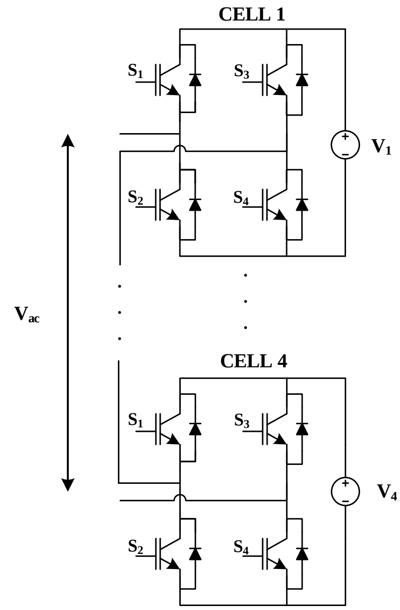


Fig. 1. Structure of a single-phase 9-level CHB converter.

4) The proposed technique can mitigate more harmonics than the conventional SHE-PWM technique.

II. Proposed Variable DC Link SHM-PWM Technique

SHM-PWM is a modulation techniques that exclusively concentrates on power quality issues and tries to satisfy main grid codes. In this paper, the goal is to use the lowest number of switchings and to satisfy the largest number of power quality standards. Moreover, a maximum number of low order harmonics will be mitigated by the proposed SHM-PWM. To reach these goals, the proposed method employs non-equal DC link voltages as degree of freedom to solve the corresponding non-linear SHM-PWM equations [30], [31].

There are several power quality standards that consider different aspects of electrical appliances that are connected to the point of common coupling (PCC). Each of these standards requires different characteristics and can be classified in two groups [4]-[7]:

1) International standards

2) Regional or National standards.

The main standards of both groups are shown in Table I. As can be seen, the international power quality standards are IEC 61000-3-6 and IEC 61000-2-12. In this paper, both of these standards are considered as the objective grid codes for the proposed SHM-PWM technique. It is worth noting that by meeting the requirements of IEC 61000-3-6 and IEC 61000-2-12, the quality standards of EN 50160 and CIGRE WG 36-05 are also satisfied.

In Table I, the grey cells show the grid code limits that are fulfilled by the proposed method. The THD of the proposed method should be lower than 6.5% up to the 50^{th} harmonic.

TABLE I

POWER QUALITY GRID CODES: INTERNATIONAL AND REGIONAL STANDARDS

Voltage Harmonic Objective	International Standards		Regional or National Standards	
Order (h)	IEC 61000-3-6	IEC 61000-2-12	EN 50160	CIGRE WG 36-05
3	4	5	5	5
5	5	6	6	6
7	4	5	5	5
9	1.2	1.5	1.5	1.5
11	3	3.5	3.5	3.5
13	2.5	3	3	3
15	0.3	0.4	0.5	0.5
17	1.6	2	2	2
19	1.2	1.76	1.5	1.5
21	0.2	0.3	0.5	0.5
23	1.2	1.41	1.5	1.5
25	1.2	1.27	1.5	1.5
27	0.2	0.2	N/A	N/A
29	1.06	1.06	N/A	N/A
31	1.01	0.97	N/A	N/A
33	0.2	0.2	N/A	N/A
35	0.91	0.83	N/A	N/A
37	0.85	0.77	N/A	N/A
39	0.2	0.2	N/A	N/A
41	0.81	0.67	N/A	N/A
43	0.78	0.62	N/A	N/A
45	0.2	0.2	N/A	N/A
47	0.73	0.55	N/A	N/A
49	0.71	0.51	N/A	N/A
THD	6.5% up to 40th	8% up to 50th	8% Up to 25th	8% Up to 25th

A. Principles of the Proposed SHM-PWM

Employing non-equal DC link voltages in the optimal selective harmonic mitigation method imposes some changes on the equations. In this method, the voltage of the DC link capacitors varies in a defined range and provides degrees of freedom for the mitigation of a larger number of harmonics. A 9-level voltage waveform with a desired number of switchings and non-equal DC link voltages is shown in Fig. 2.

From Fig. 2, the corresponding equations of the converter are derived as follows:

$$\begin{aligned} V = \sum_{m=odd} \frac{4}{m\pi} (V_1(\cos(m\theta_1) - \cos(m\theta_2) + ... + \cos(m\theta_{n1})) + \\ V_2(\cos(m\theta_{n1+1}) - \cos(m\theta_{n1+2}) + ... \\ + \cos(m\theta_{n1+n2})) + V_3(\cos(m\theta_{n1+n2+1}) \\ - \cos(m\theta_{n1+n2+2}) + ... + \cos(m\theta_{n1+n2+n3})) + \\ V_4(\cos(m\theta_{n1+n2+n3+1}) - \cos(m\theta_{n1+n2+n3+2}) + ... \\ + \cos(m\theta_{n1+n2+n3+n4}))) \sin(\omega t) \end{aligned} \quad (1)$$

where V_1, V_2, V_3, and V_4 are the DC link voltages of the CHB converter in both the single-phase and three-phase modes. θ_i represents the i^{th} switching angle of the predefined waveform. As can be seen, the number of switching angles for each cell depends on the predefined waveform. Increasing the number of switching angles can improve the quality of the output waveform. However, this reduces the converter efficiency. In the proposed approach, the lowest number of switching angles is considered for each cell of the CHB converter when the converter works in three-phase or single-phase structures.

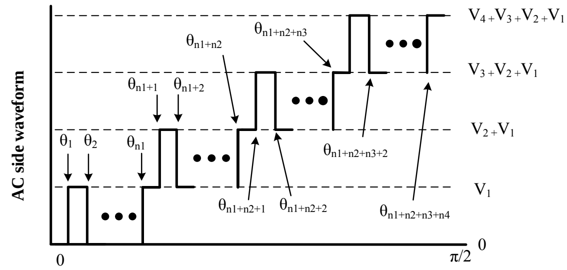


Fig. 2. Quarter period waveform of a 9-level 4-cell CHB converter with a general number of switching transitions and non-equal DC levels.

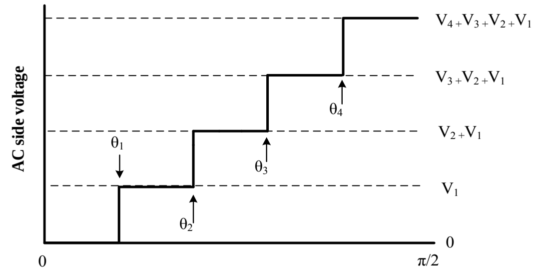


Fig. 3. Predefined waveform for a 9-level three phase CHB converter in a quarter of period.

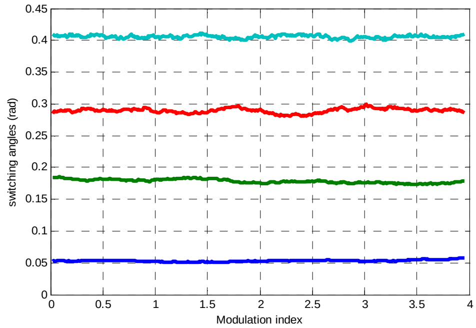
In this paper, to satisfy the aforementioned grid codes up to the 50th harmonic, a 4-cell 9-level CHB inverter is selected and the switching frequency is 50 Hz in the three-phase inverter and 150 Hz in the single-phase inverter.

B. Applying the Proposed Method in Three-Phase Structures

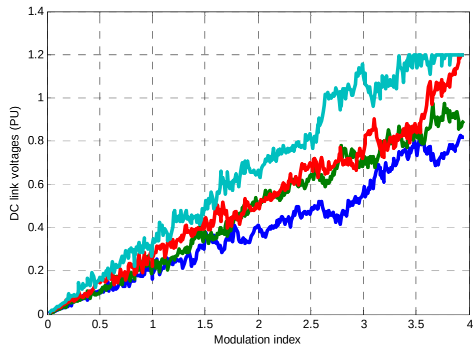
The predefined waveform for a 9-level converter with the minimum number of switching transitions in a quarter of a period is shown in Fig. 3. As can be seen in this figure, the converter has only one transition for each level of output. Thus, the modulation technique imposes a 50 Hz switching frequency for each switch of the CHB converter. The proposed method should satisfy the IEC 61000-3-6, IEC 61000-2-12, EN 50160, and CIGRE WG 36-05 power quality standards. To achieve this goal, the maximum amplitude of the non-triplen harmonics should meet the standard limits and the THD value should be lower than 6.5% up to the 50th harmonic. Meanwhile, the triplen harmonics of the output voltage are automatically eliminated due to the star connection of the CHB converter.

According to Fig. 3 and (1), the fundamental harmonic (H_1) of the predefined waveform in the three-phase mode is determined as:

$$\begin{aligned} & H_1 = \frac{4V_{DC}}{\pi}(v_1(\cos(\theta_1)) + v_2(\cos(\theta_2)) + \\ & v_3(\cos(\theta_3)) + v_4(\cos(\theta_4))) \\ & v_1 = \frac{V_1}{V_{DC}}, v_2 = \frac{V_2}{V_{DC}}, v_3 = \frac{V_3}{V_{DC}}, v_4 = \frac{V_4}{V_{DC}} \\ & 0 \le M_a \le 4, M_a = \frac{\pi H_1}{4V_{DC}} \end{aligned} \quad (2)$$



(a)



(b)

Fig. 4. Switching angles and DC link voltages as a function of modulation index (a) Switching angles (b) DC link voltages.

where v_1, v_2, v_3, and v_4 represent the normalized DC links of the converter, and M_a is the modulation index of the SHM-PWM technique. From (2), it is obvious that the acceptable solutions of the modulation technique are among 0 to 4. The other non-triplen odd harmonics (H_i), which should be controlled in the proposed method, are defined as follows:

$$H_i = \frac{4V_{DC}}{i\pi}(v_1(\cos(i\theta_1)) + v_2(\cos(i\theta_2) + v_3(\cos(i\theta_3)) + v_4(\cos(i\theta_4)) \le |H_1| L_i \quad (3)$$
$$i=5,7,11,13,...,49$$

where H_i is the ith harmonic of the output voltage of the converter that should be limited to the grid code limits (L_i). Now the set of equations in (2) and (3) should be solved by a powerful algorithm. In this paper, the heuristic Particle Swarm Optimization (PSO) technique is employed. This technique has been used in several optimal modulation techniques [12], [19], [30]-[32], [34] and shows superior characteristics in comparison with other heuristic optimization methods such as Genetic Algorithm, Simulated Annealing, etc.

The obtained solutions of the equations are shown in Fig. 4. As can be seen, the DC link voltages of the converter varies from 0 to 1.2 per unit to cover almost the entire range of the modulation indices, i.e., the range from 0.01 to 3.96.

C. Applying the Proposed Method in Single-Phase Structures

In the single-phase mode, a larger number of switching

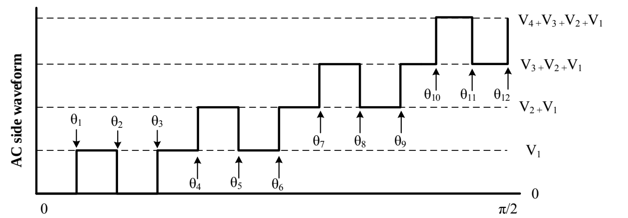


Fig. 5. Predefined switching waveform for a single-phase 9-level SHM-PWM in a quarter of period.

transitions should be considered, because the triplen harmonics have to be mitigated in this mode. In this paper, three transitions are considered for each of the switches in a quarter of a period. Thus, the switching frequency of the power switches are limited to 150 Hz in the single-phase mode. Fig. 5 shows the predefined waveform for a single-phase converter in a quarter of a period.

The fundamental harmonic equation of the predefined waveform in a single-phase inverter is obtained as:

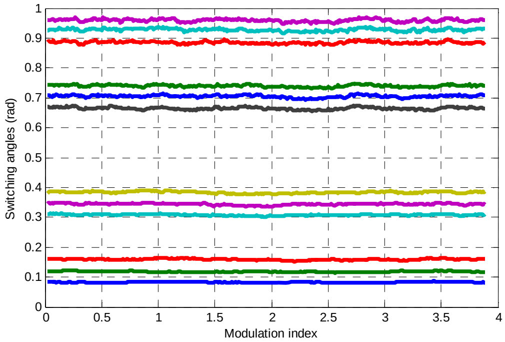
$$\begin{aligned} &H_1 = \frac{4V_{DC}}{\pi}(v_1(\cos(\theta_1) - \cos(\theta_2) + \cos(\theta_3)) \\ &+ v_2(\cos(\theta_4) - \cos(\theta_5) + \cos(\theta_6)) + v_3(\cos(\theta_7) - \cos(\theta_8) + \\ &\cos(\theta_9)) + v_4(\cos(\theta_{10}) - \cos(\theta_{11}) + \cos(\theta_{12}))), \\ &v_1 = \frac{V_1}{V_{DC}}, v_2 = \frac{V_2}{V_{DC}}, v_3 = \frac{V_3}{V_{DC}}, v_4 = \frac{V_4}{V_{DC}}, \\ &0 \le M_a \le 4, M_a = \frac{\pi H_1}{4V_{DC}} \end{aligned} \quad (4)$$

Moreover, the other odd harmonics of the predefined waveform in Fig. 5 are written as:

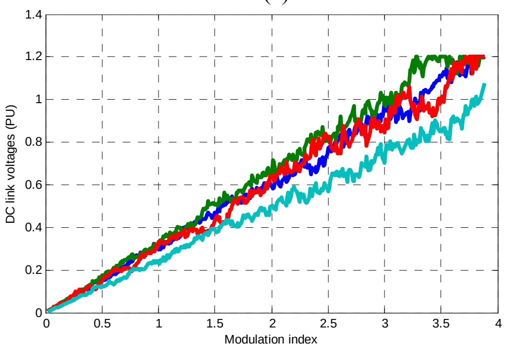
$$\begin{aligned} &H_i = \frac{4V_{DC}}{i\pi}(v_1(\cos(i\theta_1) - \cos(i\theta_2) + \cos(i\theta_3)) \\ &+ v_2(\cos(i\theta_4) - \cos(i\theta_5) + \cos(i\theta_6)) \\ &+ v_3(\cos(i\theta_7) - \cos(i\theta_8) + \cos(i\theta_9)) \\ &+ v_4(\cos(i\theta_{10}) - \cos(i\theta_{11}) + \cos(i\theta_{12})) \le |H_1| L_i, \\ &i=3,5,7,9,...,49 \end{aligned} \quad (5)$$

where, the definition of the parameters in (4) and (5) are similar to those of (2) and (3). Furthermore, the voltages of the DC link sources are again limited to between 0 and 120% of the nominal value. This feature improves the range of possible solutions as a function of the modulation index. The obtained results from solving non-linear equations by the PSO algorithm are shown in Fig. 6. It can be seen from Fig. 6 that the resulting solutions cover almost the entire range of the modulation range, i.e., 0.01<Ma<3.8. More importantly, the obtained results do not have any discontinuity in the entire range and can be employed in applications which require stepwise variations in the modulation indices. In Table II, a comparison is made of the required number of switching transitions for both the conventional SHE-PWM and the SHM-PWM with equal and non-equal DC link voltages. As shown, the proposed technique in this paper can fully meet the voltage limits with the lowest number of switching transitions in each quarter period.

Applications of the proposed technique include high power



(a)



(b)

Fig. 6. Switching angles and DC link voltages as a function of modulation index (a) Switching angles (b) DC link voltages.

TABLE II

COMPARISON OF THE REQUIRED SWITCHING TRANSITION BETWEEN CONVENTIONAL MODULATION TECHNIQUES AND PROPOSED SHM-PWM TECHNIQUE TO MEET THE VOLTAGE HARMONICS UP TO 50TH FOR BOTH SINGLE- AND THREE-PHASE MODES WITH 4 CELLS IN EACH PHASE OF CHB

Modulation technique	Single-phase	Three-phase
SHE-PWM	cannot be applied	17
Non-equal SHE-PWM	21	13
SHM-PWM	cannot be applied	10
Non-equal SHM-PWM	12	4

TABLE III

CIRCUIT PARAMETERS USED FOR EXPERIMENTAL INVESTIGATION OF THE THREE-PHASE STRUCTURE

Parameter	Symbol	Value
Number of H-Bridge cells per phase	N	4
Nominal DC link voltage	V_{DC}	40V
AC side voltage frequency	F	50 Hz
Switching frequency	f_s	50 Hz
Power Switch	S	IRF540N

electronic transformers to improve the efficiency and solution range of the modulation index [25]-[39]. In addition, for distributed generations (DGs) that generate DC voltages, a DC/AC converter is required to connect to grid or loads. This converter can use the proposed modulation technique to inject active and reactive powers to the power grid and ac loads, when all of the power quality voltage limits are met.

III. SIMULATION AND EXPERIMENTAL RESULTS OF THE PROPOSED APPROACH

In this section, simulation and experimental results of the proposed method are investigated, when a 9-level CHB converter is employed. MATLAB/Simulink software is used for obtaining the simulation results in both the single-phase and three-phase modes. For hardware implementation, IGBT or Power MOSFET switches can be used in the CHB configurations. In this paper, Power MOSFET switches have been employed. A picture of the hardware prototype of the CHB converter is shown in Fig. 7. In the hardware setup, a CORTEX M4 ARM processor is employed to generate the SHM-PWM switching pattern. Moreover, four DC power supplies are used to simulate the behavior of the DC/DC converters.

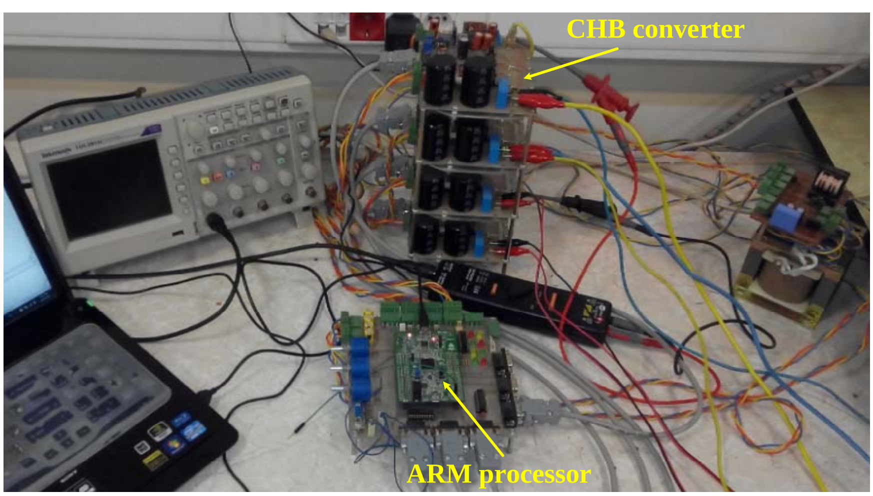


Fig. 7. Hardware prototype of the single-phase 9-level CHB converter.

A. Investigation of the Three-Phase Mode

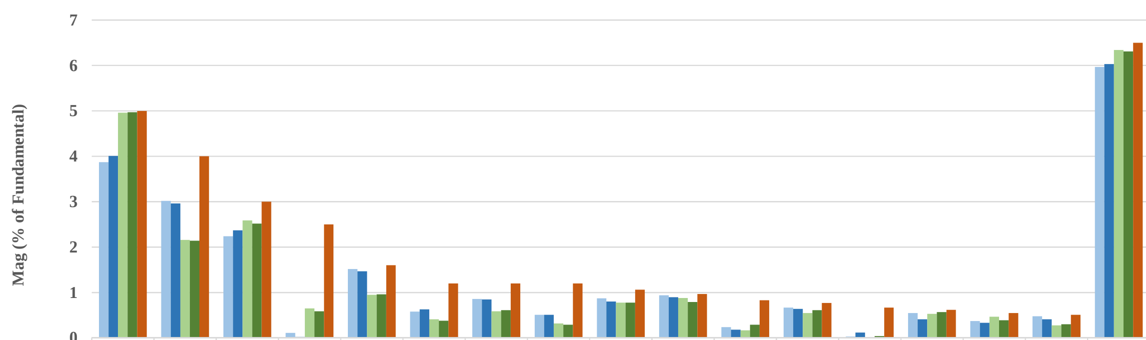
The circuit parameters of the proposed method are shown in Table III. To verify the validity of the proposed method, two operating points, which have the lowest (the best) and highest (the worst) THD values, are simulated and implemented in the three-phase mode. The lowest amount of THD is obtained when the modulation index is 0.76 and the switching angles are 0.0538, 0.1799, 0.2907, and 0.4083 radian for the first, second, third, and fourth cells, respectively. The DC link voltages are 0.1556, 0.1665, 0.1883, and 0.2834 per-unit for the first, second, third, and fourth cells, respectively.

The same experimental implementation is carried out on the worst operating point $M_a=2.51$. The switching angles (Rad) and the DC link voltages (p.u) are $\theta_1=0.0537$, $\theta_2=0.1776$, $\theta_3=0.2844$, $\theta_4=0.4054$, $v_1=0.49275$, $v_2=0.6374$, $v_3=0.6869$, and $v_4=0.8000$. To compare the simulation results with those of the experiments, both sets of results are displayed in Fig. 8. As can be seen, the obtained results satisfy the grid codes (EN 50160, CIGRE WG 36-05, IEC 61000-3-6 and IEC 61000-2-12) represented in Table I by employing one switching transition in each quarter of a period. In Fig. 11(a), the obtained result of the point with the highest THD (worst condition) is shown.

In Fig. 9, a comparison of the SHM-PWM and SHE-PWM is presented to show the advantage of the SHM-PWM. It is obvious that the 25th, 29th, 47th, and 49th harmonic orders and the THD cannot meet the grid codes with the SHE-PWM technique. However, with the SHM-PWM, all of the harmonics and the THD can satisfy the requirements of the grid codes in Table I.

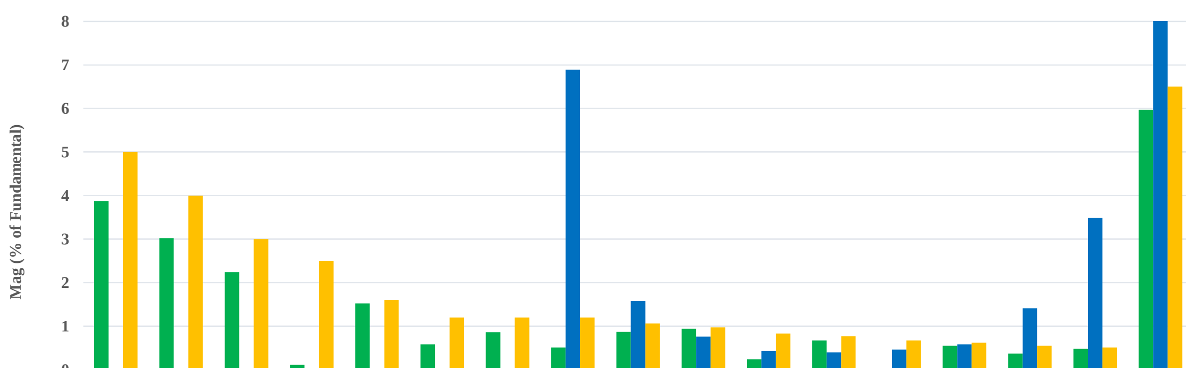
B. Investigation of the Single-Phase Mode

The validity of the single-phase mode is confirmed in this section. In the single-phase mode, all of the odd harmonics including the triplen harmonics should be limited to extreme values. The circuit parameters are same as those of the previous investigation except for the switching frequency which is 150 Hz. In this mode, the operating points with the



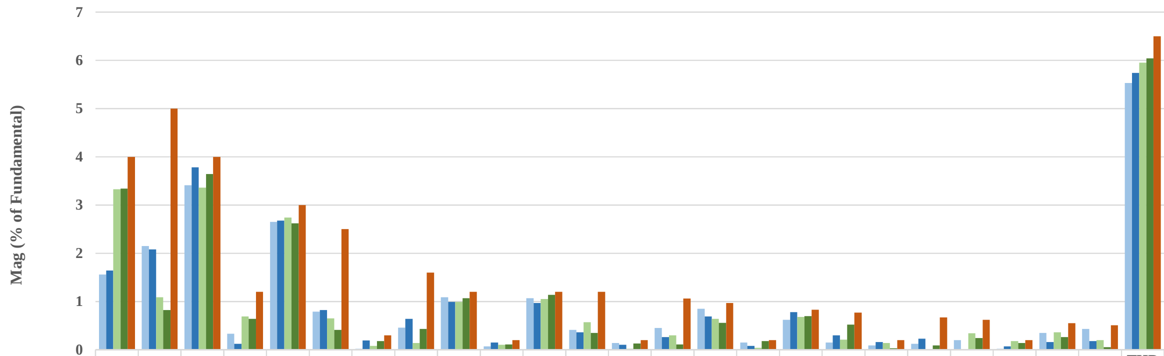
Harmonic	5	7	11	13	17	19	23	25	29	31	35	37	41	43	47	49	THD (50th)
Best Case (simulation)	3.87	3.02	2.24	0.11	1.52	0.58	0.86	0.51	0.87	0.94	0.24	0.67	0.03	0.55	0.37	0.48	5.97
Best Case (experimental)	4.01	2.96	2.37	0.02	1.47	0.63	0.85	0.51	0.8	0.9	0.18	0.64	0.12	0.41	0.33	0.41	6.03
Worst Case (simulation)	4.96	2.16	2.59	0.65	0.95	0.41	0.59	0.32	0.78	0.88	0.17	0.55	0.01	0.53	0.47	0.28	6.34
Worst Case (experimental)	4.97	2.14	2.52	0.59	0.96	0.38	0.61	0.29	0.78	0.79	0.29	0.61	0.04	0.57	0.39	0.3	6.31
Grid Code Limits	5	4	3	2.5	1.6	1.2	1.2	1.2	1.06	0.97	0.83	0.77	0.67	0.62	0.55	0.51	6.5

Fig. 8. Comparing the harmonic values in simulation and experimental results (three-phase mode).



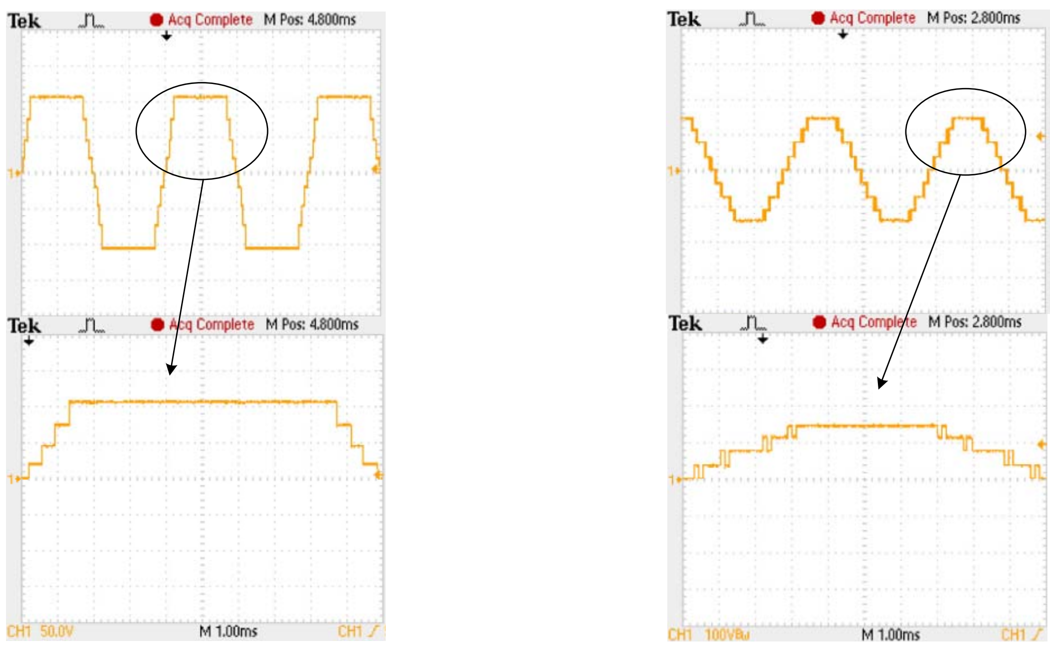
Harmonic	5	7	11	13	17	19	23	25	29	31	35	37	41	43	47	49	THD (50th)
SHM	3.87	3.02	2.24	0.11	1.52	0.58	0.86	0.51	0.87	0.94	0.24	0.67	0.03	0.55	0.37	0.48	5.97
SHE	0	0	0	0	0	0	0	6.89	1.58	0.76	0.43	0.4	0.46	0.58	1.41	3.49	8.1
Grid Code Limits	5	4	3	2.5	1.6	1.2	1.2	1.2	1.06	0.97	0.83	0.77	0.67	0.62	0.55	0.51	6.5

Fig. 9. Comparing the harmonic values in SHE and SHM (Best case).



Harmonic	3	5	7	9	11	13	15	17	19	21	23	25	27	29	31	33	35	37	39	41	43	45	47	49	THD (50th)
Best Case (simulation)	1.56	2.15	3.41	0.33	2.65	0.79	0.02	0.46	1.09	0.07	1.07	0.41	0.14	0.45	0.85	0.15	0.62	0.15	0.09	0.12	0.2	0.02	0.35	0.43	5.53
Best Case (experimental)	1.64	2.08	3.78	0.12	2.68	0.82	0.19	0.64	0.99	0.15	0.97	0.36	0.1	0.26	0.69	0.08	0.78	0.3	0.16	0.23	0.01	0.07	0.16	0.18	5.74
Worst Case (simulation)	3.33	1.09	3.36	0.69	2.74	0.65	0.08	0.14	0.99	0.1	1.05	0.57	0.02	0.3	0.64	0.04	0.68	0.21	0.14	0	0.34	0.18	0.36	0.2	5.95
Worst Case (experimental)	3.34	0.82	3.64	0.64	2.62	0.41	0.18	0.43	1.07	0.11	1.14	0.35	0.13	0.11	0.56	0.18	0.7	0.52	0.03	0.09	0.24	0.14	0.26	0.05	6.04
Grid Code Limits	4	5	4	1.2	3	2.5	0.3	1.6	1.2	0.2	1.2	1.2	0.2	1.06	0.97	0.2	0.83	0.77	0.2	0.67	0.62	0.2	0.55	0.51	6.5

Fig. 10. Comparing the harmonic values in simulation and experimental results (single-phase mode).



(a) (b)

Fig. 11. Waveform of the phase voltage synthesized by the proposed SHM-PWM. (a) In three-phase structure. (b) In single-phase structure.

lowest (the best) and highest (the worst) THD values are considered for the simulation and experimental investigations. The corresponding waveform for the best operating point is shown in Fig. 11(b), when the parameters of the converter are $M_a=2.94$; the switching angles in radian are $\theta_1=0.08069$, $\theta_2=0.1165$, $\theta_3=0.1606$, $\theta_4=0.3079$, $\theta_5=0.3434$, $\theta_6=0.3837$, $\theta_7=0.6676$, $\theta_8=0.7078$, $\theta_9=0.74377$, $\theta_{10}=0.8920$, $\theta_{11}=0.9296$, $\theta_{12}=0.9662$; and the DC link voltages in p.u. are $v_1=0.8879$, $v_2=0.9848$, $v_3=0.88676$, and $v_4=0.7722$. On the other hand, the worst operating point has a modulation index of $M_a=1.43$; and the switching angles (Rad) and DC link voltages (p.u) are $\theta_1=0.08296$, $\theta_2=0.11657$, $\theta_3=0.1584$, $\theta_4=0.3075$, $\theta_5=0.3460$, $\theta_6=0.3831$, $\theta_7=0.6631$, $\theta_8=0.7055$, $\theta_9=0.7404$, $\theta_{10}=0.8894$, $\theta_{11}=0.9262$, $\theta_{12}=0.9620$, $v_1=0.4604$, $v_2=0.49392$, $v_3=0.3698$, and $v_4=0.3768$. In Fig. 10, a comparison of simulation and experimental results for the best and worst operating points is shown. It can be seen that the proposed method successfully satisfies the mentioned grid codes and that the switching frequency is 150 Hz.

IV. CONCLUSIONS

In this paper, a low frequency modulation technique was proposed for multilevel CHB inverters. The proposed method satisfies two international power quality standards (IEC 61000-3-6, and IEC 61000-2-12) and two regional power quality standards (EN 50160, and CIGRE 36-05). Moreover, it has the lowest number of switching transitions in the three-phase mode (one transition for each switch in a fundamental period). Thus, it has the highest efficiency which can be achieved in a 9-level CHB converter. Furthermore, the proposed method mitigates all of the odd harmonics including the triplen harmonics in single-phase converters by three switching transitions for each of the switches in a fundamental period. The proposed method is based on adjustable DC links in order to have a continuous answer set for the entire range of modulation indices. More importantly, the THD of the proposed method in both the single-phase and three-phase modes is lower than 6.5% up to the 50th harmonic.

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