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Asymmetrical PWM for Harmonics Reduction and Power Factor Improvement in PWM AC Choppers Using Bee Colony Optimization

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Abstract

This paper presents the application of bee colony optimization (BCO) to obtain the optimal switching angles for single phase PWM AC choppers. The optimal switching angles are found in the region of 0-π based on the asymmetrical PWM technique. This PWM process results in improvements of the total harmonic distortion of the output voltage and in the input power factor. Simulation and experimental results are compared with the conventional PWM to verify the performance of the proposed PWM process.

Key words: Asymmetrical Pulse Width Modulation, Harmonic reduction, Power Factor Improvement, PWM AC chopper, Bee Colony Optimization

I. Introduction

AC choppers have been widely used in many applications such as lighting, heating and soft start motor controllers [1]. Generally, there are two methods for varying the AC output voltage from a fixed AC voltage source. The first method is the phase angle control. The AC output voltage average of this method is controlled by the firing angle of the power switches [2]. Because of its simple configuration and thyristor-based switches, this method has the advantages of simple control circuit and the ability to controlling a large amount of economical power. However, it faces a delay of the firing angle which results in a discontinuation of the power flow at both the input and output sides and significant harmonics in the load current. The second method is to employ pulse width modulation (PWM) to control the power switches. This process produces an input current that is nearly sinusoidal, which results in a low total harmonic distortion, THD_{ii}. As for the phase angle, this process depends on the phase angle of the output current. This means that the input power factor, PF_i, depends on the load power factor, PF_o. However, the input power factor of this method is still higher than that of the phase angle control method [1].

In general, the PWM AC choppers for high power applications have a switching frequency that is fixed and low. This means that the PWM signal can be modified to achieve a better PF_i or total harmonic distortion of the output voltage, THD_{vo}. Many techniques have been proposed to improve the PWM performance of high PF_i. The references and the carrier signals are modified [3]-[5].

Recently, artificial intelligent techniques have been used to find the optimal switching angles of PWM patterns. They have been obtained with the use of a genetic algorithm (GA) [7], [8], particle swarm optimization (PSO) [9], [10], artificial neural network (ANN) [11], genetic algorithm and artificial neural network [12], [13], particle swarm optimization and artificial neural network [14], etc. However, in these papers, the solution of the switching angle is obtained in the quarter cycle 0-π/2, which may lead to a suboptimal solution. The authors of [18] applied BCO to find the optimal switching angles in the region between 0-π/2 to improve the THD_{vo}

This paper proposes an optimal switching strategy based on BCO for PWM AC choppers. In this approach, BCO is adopted to obtain the optimal switching angles of the PWM pattern by considering the region between 0-π. The proposed approach aims to minimize the harmonic distortion of the converter's output voltage while satisfying the technical

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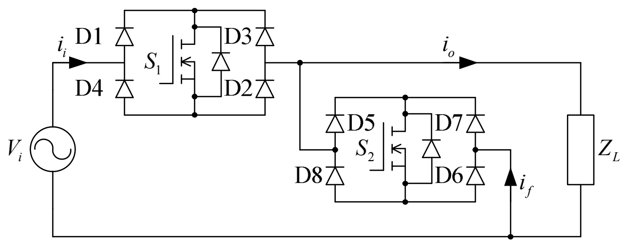

Fig. 1. Single phase AC Choppers.

constraints of the switching angle sequences. The results of previous work will be compared to the method proposed in this paper. In addition, experiments with a 770W AC-AC converter are used to confirm the performance of the proposed switching pattern in terms of reducing the THD_{vo} and improving the PF_i .

This paper is organized as follows. Section II describes the background of PWM AC choppers and presents the BCO concept. Section III expresses the problem formulation of the optimal switching strategy. Section IV proposes the BCO algorithm to provide the optimal PWM switching patterns. Sections V and VI show the simulation and experimental results, respectively. And the last section is the conclusion of this paper.

II. Description and Control Techniques of AC Choppers

The power circuit of a single phase PWM AC chopper is shown in Fig. 1. Power switch S_1 performs as the switching device controlled by the PWM pattern to regulate the power delivered to the load, and switch S_2 is a free-wheeling device for stored energy transferring to the load when switch S_1 is turned off.

A. Symmetrical PWM AC Choppers

The conventional PWM is shown in Fig. 2(a). The duty cycle and the switching frequency are fixed. This PWM process is very simple and can eliminate low order harmonic contents [15]. However, the THD_o is still high and the PF_i is low, depending on the load power factor. In symmetrical pulse width modulation (SPWM), the PWM switching angles in the region 0-π/2 are symmetrical with those in the region π/2-π as shown in Fig. 2(b). These are obtained with various heuristic approaches including GA, PSO, ANN [7]-[14] and BCO [18] for the improvement of the THD_o and the PF_i. However, these techniques only meet the optimal PWM switching angles in the region 0-π/2. As a result, these approaches may lead to a suboptimal solution.

B. Asymmetrical PWM AC Choppers

Fig. 2(c) shows the waveforms of the asymmetrical pulse width modulation (APWM) method. In this process, the optimal PWM switching angles are obtained in the region 0-π.

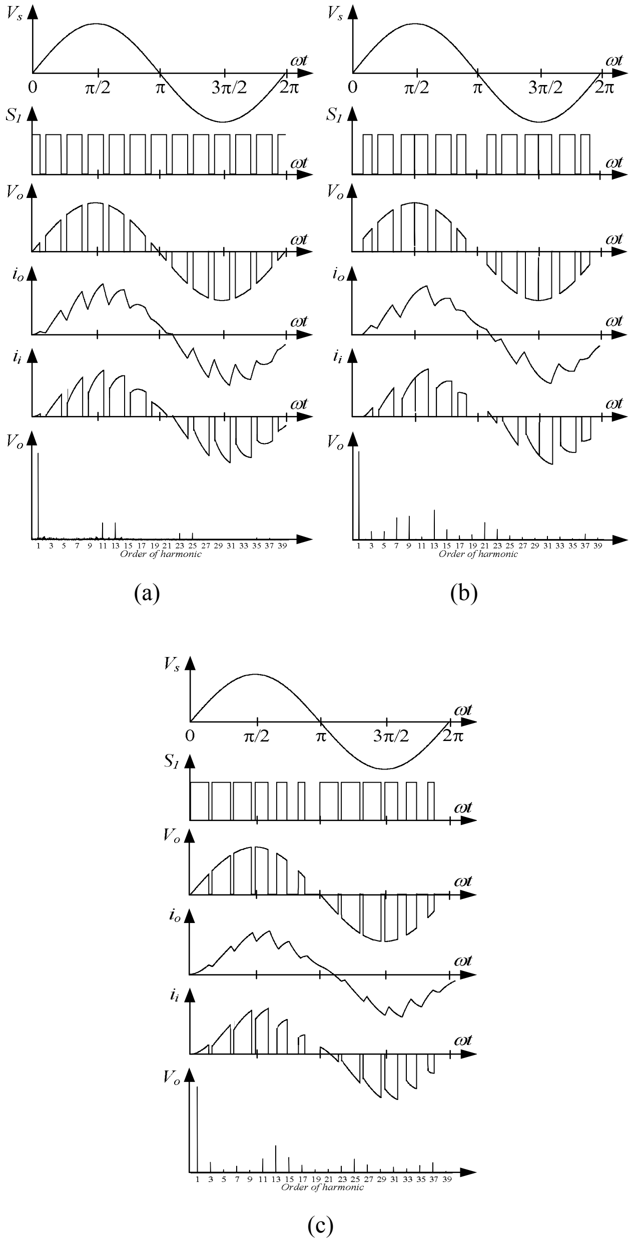

Fig. 2. Waveforms of output voltage, load current, input current and harmonic spectra of output voltage. (a) Conventional PWM. (b) SPWM Optimization technique. (c) APWM Optimization technique.

For the basic idea of this method, the PWM AC chopper waveforms are analyzed in the Fourier domain producing non-linear transcendental equations that are solved by the Newton-Raphson method [6]. However, it is difficult to determine the initial value in addressing those equations. The BCO algorithm is a very simple and robust stochastic optimization algorithm when compared with previous algorithms. In [19], the BCO algorithm was applied to find optimal PWM switching angles based on the APWM. However, the objective of this technique is only to improve the PF_i. Therefore, this paper focuses on an improvement of the THD_{vo} and the PF_i based on the BCO algorithm, using the APWM method.

C. The Circuit Equation of a PWM AC Choppers

In the ideal PWM AC chopper, the fixed input voltage is transformed by the AC-AC converter into variable output voltage v_o , the v_o and i_o can be expressed as:

$$v_o = \sqrt{2}\ V_o \sin(\omega t) \quad (1)$$

$$i_o = \sqrt{2}\ I_o \sin(\omega t) \quad (2)$$

The output voltage can be represented by the Fourier series as:

$$v_o(\omega t) = \sqrt{2}V_i \sum_{n=1}^{\infty} \{A_n \sin(n\omega t) + B_n \cos(n\omega t)\} \quad (3)$$

The fundamental coefficients, A_1 and B_1, are expressed as:

$$A_1 = \frac{1}{\pi}\sum_{k=1}^{M}\left[(\beta_k - \alpha_k) - \frac{\sin(2\beta_k) - \sin(2\alpha_k)}{2}\right] \quad (4)$$

$$B_1 = \frac{1}{\pi}\sum_{k=1}^{M}\left[\frac{\cos(2\alpha_k) - \cos(2\beta_k)}{2}\right] \quad (5)$$

The harmonic coefficients, A_n and B_n, are expressed as:

$$A_n = \frac{1}{\pi}\sum_{k=1}^{M}\left[\frac{\sin\{(n-1)\beta_k\} - \sin\{(n-1)\alpha_k\}}{(n-1)} - \frac{\sin\{(n+1)\beta_k\} - \sin\{(n+1)\alpha_k\}}{(n+1)}\right] \quad (6)$$

$$B_n = \frac{1}{\pi}\sum_{k=1}^{M}\left[\frac{\cos\{(n-1)\beta_k\} - \cos\{(n-1)\alpha_k\}}{(n-1)} - \frac{\cos\{(n+1)\beta_k\} - \cos\{(n+1)\alpha_k\}}{(n+1)}\right] \quad (7)$$

The output voltage of (3) is rewritten as:

$$v_o(\omega t) = \sqrt{2}V_i \sum_{n=1}^{\infty} C_n \sin(n\omega t + \phi_{rn}) \quad (8)$$

Where, $C_n = \sqrt{A_n^{\ 2} + B_n^{\ 2}}$ and $\phi_{rn} = \tan^{-1}(B_n / A_n)$

Therefore, the output current is rewritten as:

$$i_o(\omega t) = \sqrt{2}V_i \sum_{n=1}^{\infty} \frac{C_n}{\sqrt{R^2 + (nX)^2}} \sin(n\omega t + \phi_{rn} - \phi_{on}) \quad (9)$$

Where, $X = \omega L$ and $\phi_{on} = \tan^{-1}(nX/R)$. It is assumed that I_{on} and V_{on} are the rms values of n^{th} harmonic content of the output current and voltage, respectively. Thus, the *THD* of the output current and voltage are defined as:

$$THD_i = \frac{\sqrt{\sum_{n=3}^{\infty} I_{on}^2}}{I_{o1}} \quad (10)$$

$$THD_v = \frac{\sqrt{\sum_{n=3}^{\infty} V_{on}^2}}{V_{o1}} \quad (11)$$

Where n = 3, 5, 7…

Therefore, the input power factor (PF_i) can be expressed as:

$$PF_i = \frac{\cos\phi_{in}}{\sqrt{1 + THD_i^2}} \quad (12)$$

III. PROBLEM FORMULATION

To find the optimal APWM switching pattern for reducing total harmonic distortions, the objective function to minimize the total harmonic distortions can be written as:

$$\underset{\alpha,\beta}{Min}\ F = \sqrt{\left[\ (C_1 - V_{o,ref})^2 + C_3^2 + C_5^2 + \ldots + C_n^2\ \right]} \quad (13)$$

Subject to:

$$\alpha_1 \le \beta_1 \le \alpha_2 \le \beta_2 \le \ldots\ldots \le \alpha_n \le \beta_n \le \pi \quad (14)$$

Where, C_1 is the fundamental coefficient of the output voltage, $V_{o,ref}$ is the reference output voltage, α and β are the turn-on and turn-off switching angle, and $\alpha_1 = 0$. The new search pattern proposed in this paper has some features that reduce the total harmonic distortion and improve the input power factor.

IV. PROPOSED SOLUTION ALGORITHM

The BCO algorithm imitates the intelligent behaviors of the bee found in the nature. There are two types of bees namely; scout bees and worker bees. The scout bees search for sources of nectar and return to the hive. After that, they perform a waggle dance, which notifies the direction, distance from the hive and the quality of the nectar to the worker bees. The worker bees bring nectar to the hive, a large number of them can collect more nectar from good sources than from other sources [16], [17].

In this paper, the BCO algorithm has been used in finding the APWM switching patterns. The solution is shown in Fig. 3 and it is obtained as follows:

1. Determine appropriate parameters, which include the number of scout bees (n), number of sites selected out of n visited sites (m), number of best sites out of m selected sites (e), number of bees recruited for the best e sites (n_{ep}), number of bees recruited for the other m-e selected sites (n_{sp}), initial size of the patches (n_{gh}) and stopping criteria, and determine the parameters of AC voltage controller such as M and V_{oref}.

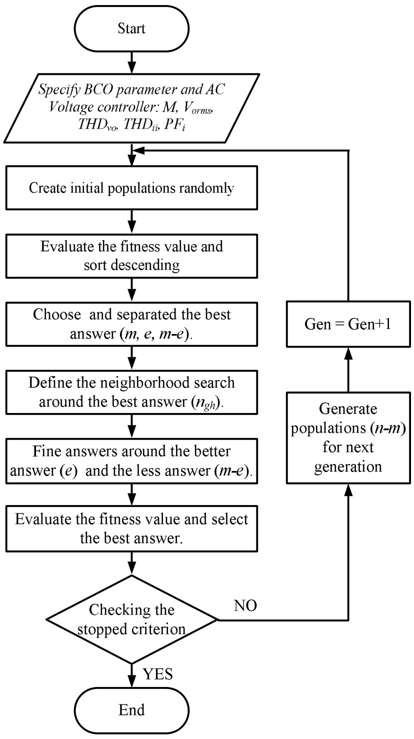

Fig. 3. Proposed BCO algorithm.

2. Order the scout bees (n) to random switching angles (α and β), with constraint satisfaction by equation (15) and (16).

$$\alpha_i = \alpha_{i-1} + (\pi / M) \tag{15}$$

$$\beta_i = \alpha_i + \left[(\pi i / M) - \alpha_i\right] \times rand(0,1) \tag{16}$$

Where, M is the number of pulses per half cycle of the APWM waveform and i = 1 to M.

3. Evaluate the fitness value obtained from the scout bees by equation (17) and sort in descending order.

$$Fitness = 1 - F \tag{17}$$

4. Choose the best answer (m) and separate into 2 groups (e, m-e).
5. Define the neighborhood search around the best answer (n_{gh}).
6. Order the worker bees (n_{ep}) to find answers around the better answer (e) and order the workers bees (n_{sp}) to find answers around the less good answer (m-e).
7. Evaluate the fitness value obtained from the worker bees by equation (17) and select the best answer.
8. Check the stop criterion. If the process is not stoped, proceed the iteration as needed.
9. Order the scout bees (n-m) to random switching angles (α and β) by equation (14) to (16) and return to 3.

V. Simulation Results

The designed PWM AC chopper is simulated by several software packages. The optimal PWM switching angles are obtained by the MATLAB program. While the designed PWM chopper is simulated by the Pspice program with the following system parameters: V_i = 220 V_{rms}, f_i = 50 Hz, R_o = 240 Ω, L = 300 mH and M = 6 pulses, at a load power factor of 0.9308 lagging.

TABLE I
Parameters of BCO Algorithm

Parameters	Number
Number of scout bees (n)	20
Number of selected sites (m)	14
Number of best sites (e)	10
Number of recruited bees for the best e sites (n_{ep})	20
Number of recruited bees for other Sites (n_{sp})	10

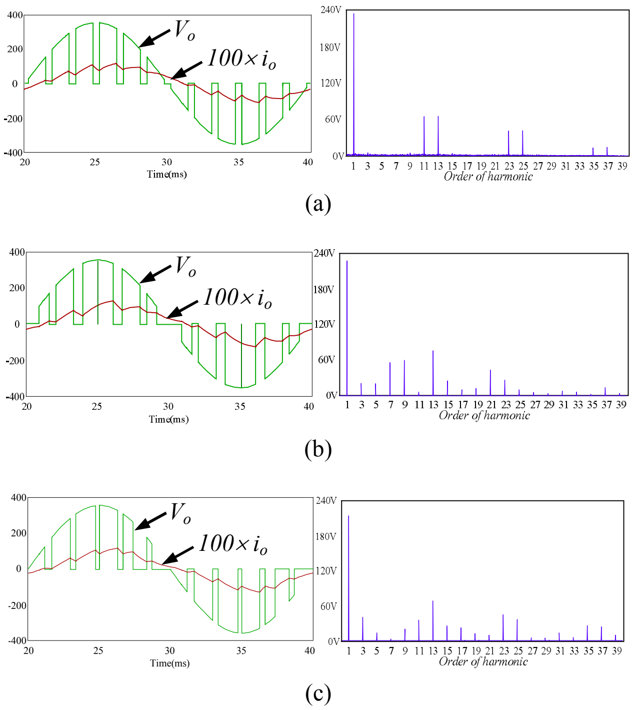

Fig. 4. Waveforms of the output voltage, load current and output voltage harmonic spectrum at output voltage 160 V_{rms}. (a) Conventional PWM technique. (b) BCO SPWM technique. (c) Proposed APWM technique.

A. Optimal Switching Angle Solution

For the BCO algorithm, the required parameters are listed in Table I. The BCO parameters are selected from an empirical examination with a reasonable computational cost. This affects both the convergence characteristic and the computational efficiency. The turn-on switching angles (α_n) are set at 0, 30, 60, 90, 120 and 150 degrees. The optimal turn-off switching angles (β_n) at various output voltage levels are shown in Table II.

The optimal turn-off switching angles at various output

TABLE II
OPTIMAL TURN-OFF SWITCHING ANGLES OBTAINED BY BCO ALGORITHM AT VARIOUS OUTPUT VOLTAGE LEVELS

Output Voltage (V)	Optimal turn-off switching angles (degree)					
	β_1	β_2	β_3	β_4	β_5	β_6
150	21.647	49.912	80.511	112.326	141.735	151.266
160	25.979	59.576	79.933	111.444	134.643	150.972
170	27.900	58.530	84.0303	108.382	143.306	151.022
180	23.860	58.501	84.091	112.811	149.060	150.759
190	26.232	57.601	85.322	116.745	147.837	151.954
200	28.794	59.399	86.497	117.070	149.604	153.454

$\alpha_1 = 0$, $\alpha_2 = 30$, $\alpha_3 = 60$, $\alpha_4 = 90$, $\alpha_5 = 120$, $\alpha_6 = 150$ degrees

TABLE III
PERFORMANCE OF THE CONVENTIONAL PWM, BCO SPWM TECHNIQUE [18] AND PROPOSED APWM TECHNIQUE AT LOAD POWER FACTOR 0.9308 ($Z = 240 + j300\Omega$) AND $V_O = 160$ V_{RMS}.

Method	Input		Output	
	THD_{ii}	PF_i	THD_{io}	THD_{vo}
Conventional PWM	0.6886	0.7606	0.2122	0.6581
BCO SPWM [18]	0.6421	0.8146	0.1615	0.5744
Proposed APWM	0.5305	0.9891	0.1508	0.5395

TABLE IV
PERFORMANCE OF THE CONVENTIONAL PWM AND PROPOSED APWM TECHNIQUE AT LOAD POWER FACTOR 0.8 ($Z=50.26+j120\Omega$)

Output Voltage (V)	Conventional PWM			Proposed APWM		
	PF_i	THD_{io}	THD_{vo}	PF_i	THD_{io}	THD_{vo}
20	0.3467	0.2682	2.4110	0.9453	0.2345	2.3201
40	0.3755	0.2496	1.9635	0.9483	0.2160	1.8374
60	0.4270	0.2296	1.5297	0.9563	0.1849	1.4629
80	0.4816	0.2104	1.2324	0.9582	0.1794	1.2142
100	0.5485	0.1933	1.0345	0.9615	0.1729	0.9561
120	0.6000	0.1779	0.8625	0.9676	0.1489	0.7692
140	0.6827	0.1630	0.6901	0.9731	0.1436	0.6831
160	0.7290	0.1515	0.5637	0.9523	0.1118	0.5481
180	0.7594	0.1422	0.4156	0.9108	0.0869	0.3936
200	0.7866	0.1363	0.2054	0.8652	0.0693	0.1985

voltage levels are used in the control of the PWM AC chopper simulated by Pspice and they are shown in Table II. Fig. 4 shows the waveforms of the output voltage and load current, and the harmonic spectrum of the output voltage of (a) the conventional PWM technique, (b) the BCO SPWM technique [18] and (c) the proposed APWM technique. As can be seen in Fig. 4, the harmonics of the proposed APWM technique are distributed into low frequencies. This may be a concern in some applications. However, its THD_{vo} and PF_i are improved when compared with those of the other techniques, which is the objective of this research.

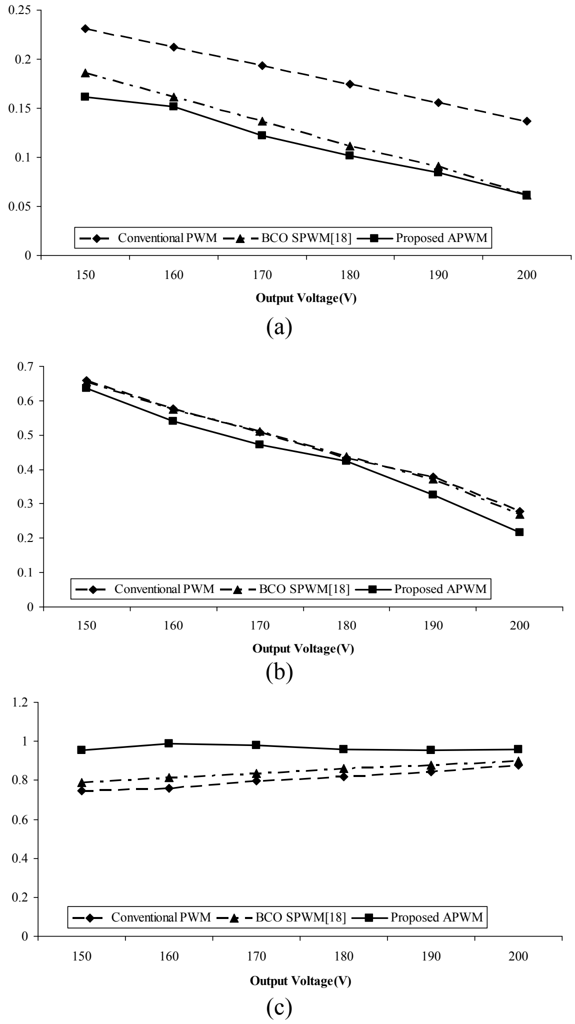

Fig. 5. THD_{io}, THD_{vo} and PF_i versus various output voltage at $PF_o = 0.9308$. (a) Total harmonic distortion of output current. (b) Total harmonic distortion of output voltage. (c) Input power factor.

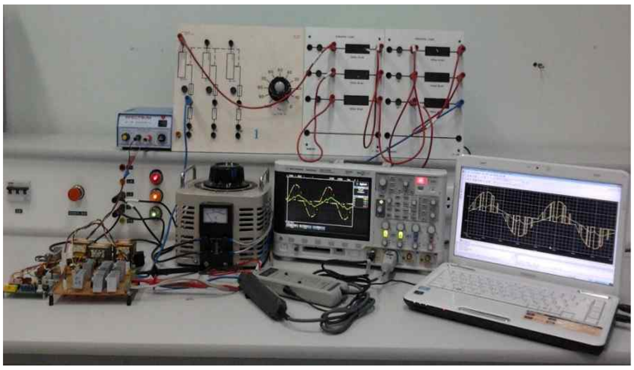

Fig. 6. Experimental prototype.

B. Comparative Results

Table III shows the simulated results of various techniques: the conventional PWM, BCO SPWM [18] and the proposed APWM techniques at an output voltage of 160 V_{rms}. The results show that the performance of proposed APWM technique in terms of the THD_{ii}, THD_{io}, THD_{vo} and PF_i is

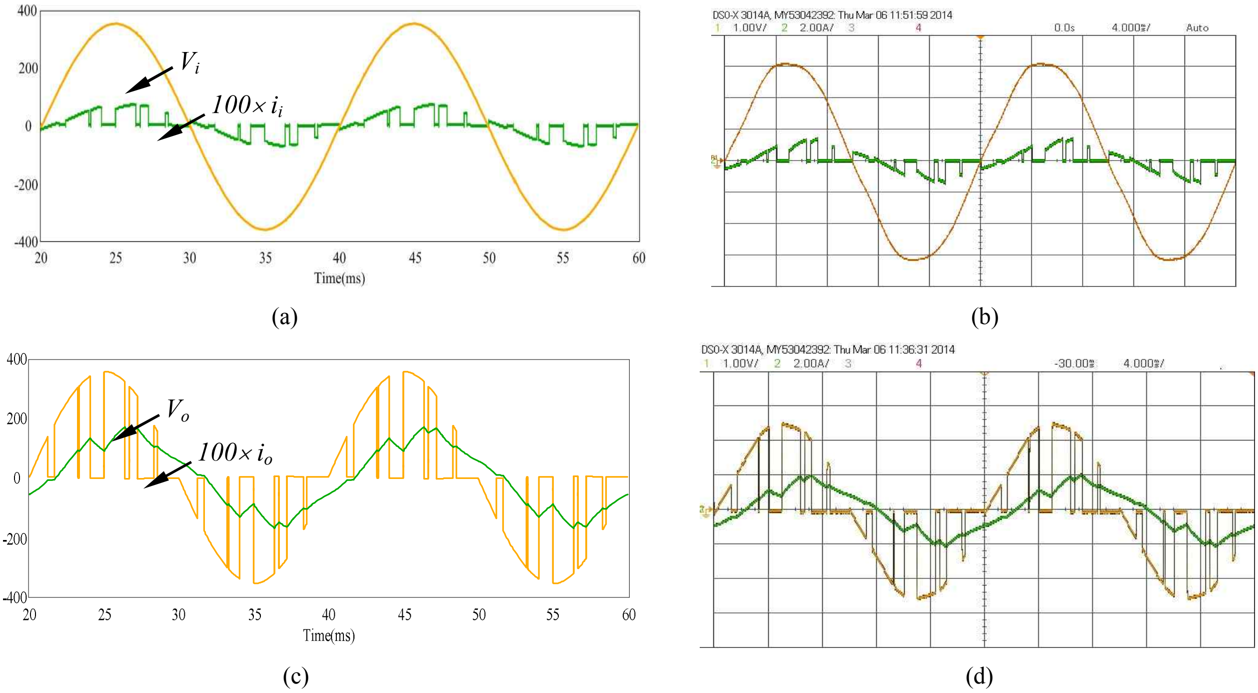

Fig. 7. Simulation and experimental results: current and voltage at V_o = 140 V_{rms}. (a)-(b) input side. (c)-(d) output side. (voltage, 100 V/div, current, 2 A/div, 4 ms/div).

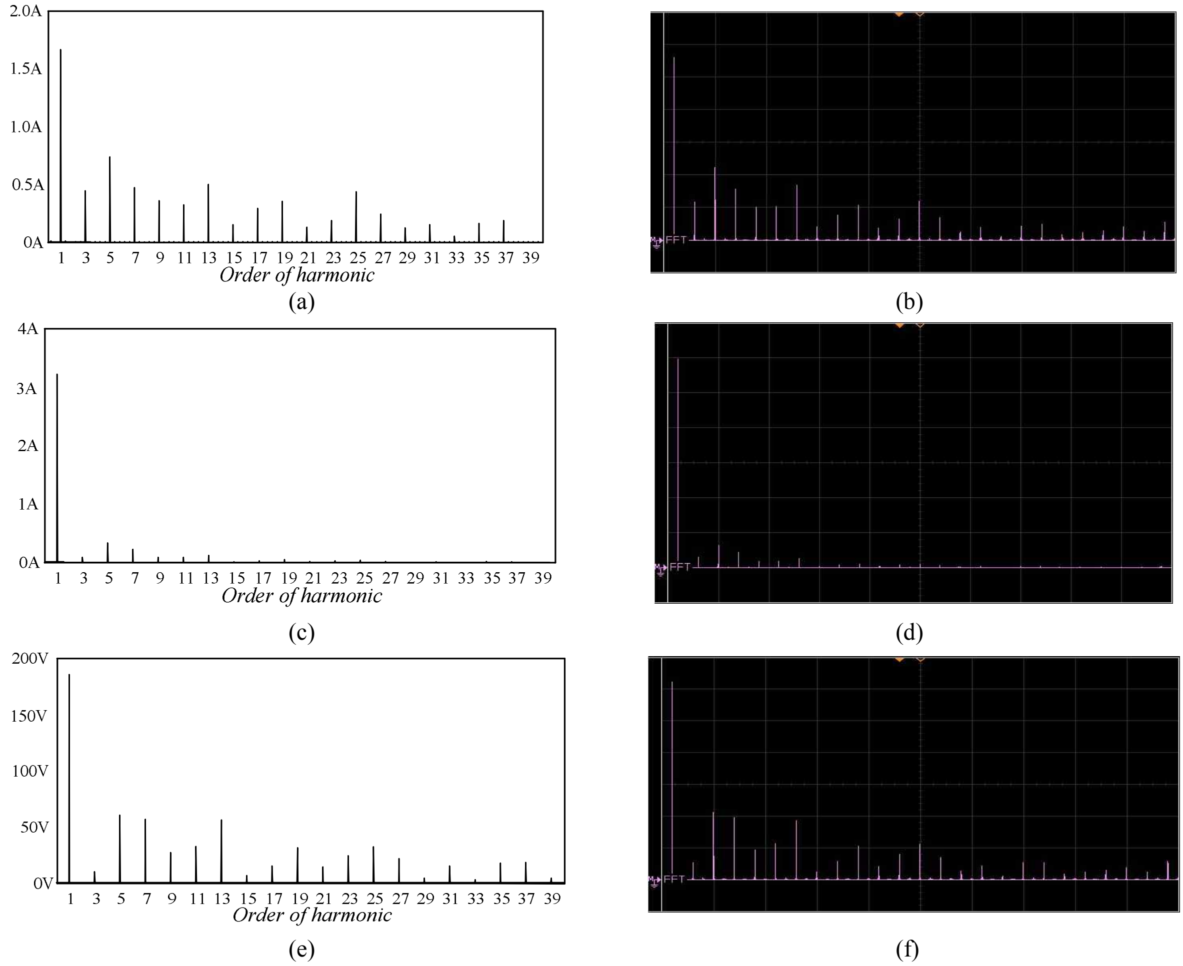

Fig. 8. Simulation and experimental results of harmonic spectra of the current and voltage at V_o = 140 V_{rms}. (a)-(b) THD_{ii} . (c)-(d) THD_{io}. (e)-(f) THD_{vo}. (voltage, 50 V/div, current, 1 A/div, 500 ms/div).

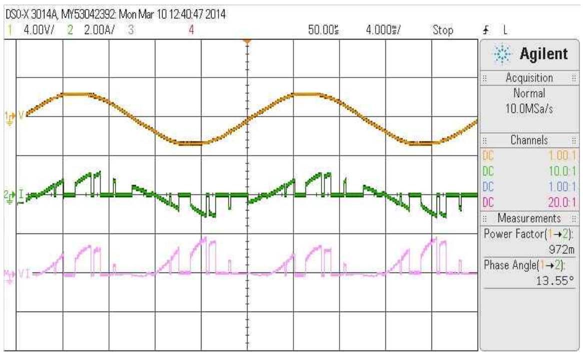

Fig. 9. Waveforms of an experimental result at V_o = 140 V_{rms}. (voltage, 400 V/div, current, 2 A/div, 4 ms/div).

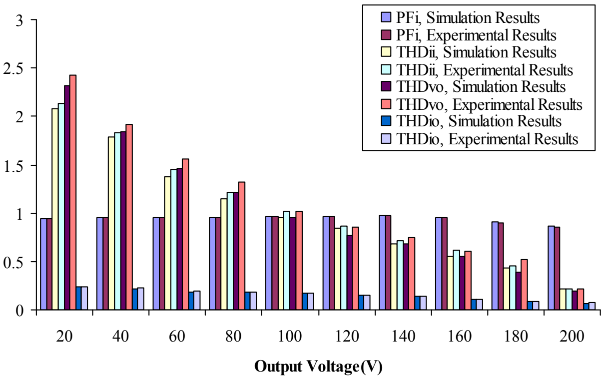

Fig. 10. Comparison between simulation and experimental results of PF_I,THD_{II}, THD_{VO} AND THD_{IO}.

better than that of the other techniques. Fig. 5 shows simulated results at various output voltage levels. The THD_{io} and THD_{vo} of the proposed technique (Fig. 5(a) and 5(b)) are significant low when compared with the other techniques for all of the output voltage levels. The PF_i results are shown in Fig. 5(c). They show that the PF_i of the proposed APWM technique is higher than those of the other techniques.

Table IV shows a performance comparison between the proposed APWM technique and the conventional PWM technique at V_i = 220 V_{rms}, f_i = 50 Hz and a load power factor that is 0.8 lagging (Z=50.26+j120Ω). As shown in this table, the proposed APWM technique has a better performance than the conventional PWM technique at all of the output voltage levels, especially, in case of the PF_i .

VI. EXPERIMENTAL RESULTS

This section shows experimental results to confirm the performance of the proposed APWM technique. Fig. 6 shows the experimental prototype used in the laboratory. The system parameters are specified as follows: V_i = 220 V_{rms}, f_i = 50 Hz, R_o = 50.26 Ω, L = 120 mH and M = 6 pulses at a load power factor that is 0.8 lagging. The PIC microprocessor is programmed to generate the APWM switching patterns for controlling the gate signals of the switching devices. The turn-on switching angles are set as follows: 0, 30, 60, 90, 120 and 150 degrees. The optimal turn-off switching angles are equal to 22.2779, 58.1004, 72.9212, 114.7289, 129.7994 and 153.674 degrees at an output voltage of 140 V.

Fig. 7 shows a comparison between the simulation and experimental waveforms of the input voltage/current and output voltage/current at an output voltage of 140 V_{rms}. It can be seen that the experimental results are consistent with the simulation results.

Fig. 8 shows the simulation and experimental results of the harmonic spectra of the input current, output current and output voltage. The measurements of the THD_{ii}, THD_{io} (Total harmonic distortion of the output current) and THD_{vo} are 71.05% 14.24% and 74.24%, respectively.

Fig. 9 shows the waveforms of the experiment at V_o = 140 V_{rms} where the PF_i is equal to 0.972. From these results, it can be seen that the proposed APWM technique is able to improve the PF_i which higher than the load power factor (0.8).

Fig. 10 shows the PF_i, THD_{ii}, THD_{vo} and THD_{io} of the proposed technique at various output voltage levels. It can be seen that the simulation results are consistent with the experimental results.

VII. CONCLUSIONS

This paper presents an application of BCO to obtain the optimal switching angles for single phase AC Chopper. In this technique, the switching angles are found in the region of 0-π of the sinusoidal waveform. From the simulation and experimental results, it can be seen that the performance of the proposed APWM technique is better than that the obtained by conventional PWM and SPWM techniques, especially, in the case of the output voltage-input current harmonic distortion and the input power factor. However, in the proposed technique, the harmonics still distribute at low frequencies. This problem should be considered in future work.

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