

Various Types of Particle Swarm Optimization-based Methods for Harmonic Reduction of Cascade Multilevel Inverters for renewable energy sources

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ABSTRACT: The use of multilevel inverters in renewable energy such as fuel cell, solar cell, and wind turbines, which use converters, is becoming more prominent. Therefore, the harmonic reduction concept in these inverters is being considered. In this paper, three algorithms (particle swarm optimization (PSO), modified particle swarm optimization (MPSO), and weight improved particle swarm optimization (WIPSO)) are used to determine the optimum switching angles of cascade multilevel inverters for obtaining minimum voltage total harmonic distortion (THD) in a wide range of modulation index. To reduce the THD, selective harmonics should be eliminated by optimal switching angles. In this paper, five switching angles of an Eleven-Level H-bridge inverter are determined by the three mentioned algorithms to reduce the voltage THD. The derived equations for the computation of output voltage THD of an inverter are used as the objective function. This objective function is used to minimize the THD in the output voltage of an inverter. While minimizing the objective function, the selective harmonics such as the 5th, 7th, 11th and 13th can be controlled by using the PSO, MPSO, and WIPSO algorithms. The simulations are performed for an 11 level cascaded multilevel inverter to show the validity of the proposed methods. The results show that all three proposed algorithms can eliminate selective harmonic in optimization problem and output voltage THD decreases. Generally, the WIPSO algorithm finds the answer with less iteration and with higher speed convergence among the proposed methods. The performance of the three mentioned algorithms for THD reduction depends on amplitude modulation index (M). MPSO and WIPSO algorithms have lower iteration numbers than PSO algorithm. Also WIPSO algorithm has higher speed convergence among the proposed methods. All three proposed algorithms reduce the 5th, 7th, 11th and 13th order harmonics in optimization problem.

KEYWORDS: Multilevel inverter, Particle swarm optimization (PSO), Modified particle swarm optimization (MPSO), Weight improved particle swarm optimization (WIPSO).

1 INTRODUCTION

Multilevel inverters can be used to interconnect several renewable energy sources such as solar, fuel cell, and/or rectified output of wind energy with the AC grid [1]. Harmonic disturbances cause different types of damage to different types of electrical equipment [2]. In order to improve the performance and increase the efficiency of inverter's output voltage waveform, the harmonic reduction problem is increased. The multilevel inverters have a good structure to reach high quality and high power rating output waveforms by reasonable dynamic responses [3-4]. Multilevel converters have different power circuit topologies. The cascade connection is the most used power circuit topology of multilevel converters [5]. S number of single-phase full-bridge inverters generate $(2S + 1)$ number of levels. In [6-7], two various modulation methods such as sinusoidal pulse width modulation (SPWM) and space-vector PWM (SVPWM) techniques are used to control the output voltage and to eliminate the undesired harmonics in multilevel inverters with equal DC voltage source. Another approach for eliminating the specific harmonics such as the 5th, 7th, 11th and 13th in the output voltage of an inverter is to select the appropriate switching times. This method is known as Selective Harmonic Elimination (SHE) or Programmed PWM techniques [8-9]. In [10], the harmonic elimination for multilevel converters by genetic and PSO algorithms is presented. The elimination

of harmonics in a cascade multilevel inverter by considering the equality and inequality of separated DC sources by using particle swarm optimization is respectively presented at [11-12]. Selective harmonic elimination of new multilevel inverters with GA algorithm is described in [13], this method is successfully applied to five, seven and nine level inverters to find optimal switching angles. However, the quality of results decreases in high-level inverters. The PSO algorithm is applied in PWM and the multilevel inverters of both three and five DC sources to reduce the voltage THD in a wide range of modulation index and the results are compared with experimental results [14-15]. In this paper, three algorithms (particle swarm optimization (PSO), modified particle swarm optimization (MPSO), and weight improved swarm optimization (WIPSO)) are used to determine the optimum switching angles of H-bridge cascaded multilevel inverters to obtain minimum voltage total harmonic distortion (THD) in a wide range of modulation index. The objective function derived from the SHE problem is minimized using PSO, MPSO and WIPSO algorithms to calculate the switching angles without using the multiple solutions of a set of nonlinear equations. In the present approach, these algorithms search for all possible sets of solutions to minimize the total harmonic distortion, as a significant number of generations with large numbers of populations in each generation is incorporated within the algorithms. In the proposed PSO, WIPSO and MPSO algorithms, the variables are randomly initialized and the initial guess does not affect the process of solution. The present approach searches for possible minimum THD at all modulation indices, thus the problem of discontinuity of solutions at certain points is avoided. This process is repeated for PSO, WIPSO and MPSO algorithms and the results are compared between the three algorithms. The simulations are performed for an 11-level cascaded multilevel inverter to show the validity of the proposed methods. This paper is organized as follows: Section 2 represents the structure of a single-phase cascaded inverter. It In section 3, problem formulation is describe. Section 4 depicts PSO, WIPSO and MPSO algorithms and the process of applied of these algorithms to the optimization problem is also described in this section. Section 5 includes the simulation results and discussions. Section 6 presents conclusions.

2 STRUCTURE OF CASCADE MULTILEVEL INVERTERS

Figure 1(a) shows the general structure of a single-phase H-bridge cascaded multilevel inverter. Figure 1(b) shows the square output voltage waveform of multilevel inverters. The number of output phase voltage levels in a cascaded multilevel inverter is $2S+1$, where S is the number of several separate DC sources (SDCSs). This structure consists of a series connection of S single phase H-bridge cells. Each single-phase H-bridge inverter is connected to a separate DC source. These sources can be obtained from batteries, fuel cells, solar cells or ultra-capacitors. Each bridge, according to the state of four power switches, $Q1, Q2, Q3$ and $Q4$ could produce three different voltages $0, +V_{dc}$ or $-V_{dc}$. This topology has advantages such as the individual control, and protection of each bridge. Three-phase configuration model of this inverter is also available by adding another two phases and can be connected in Y or Δ .

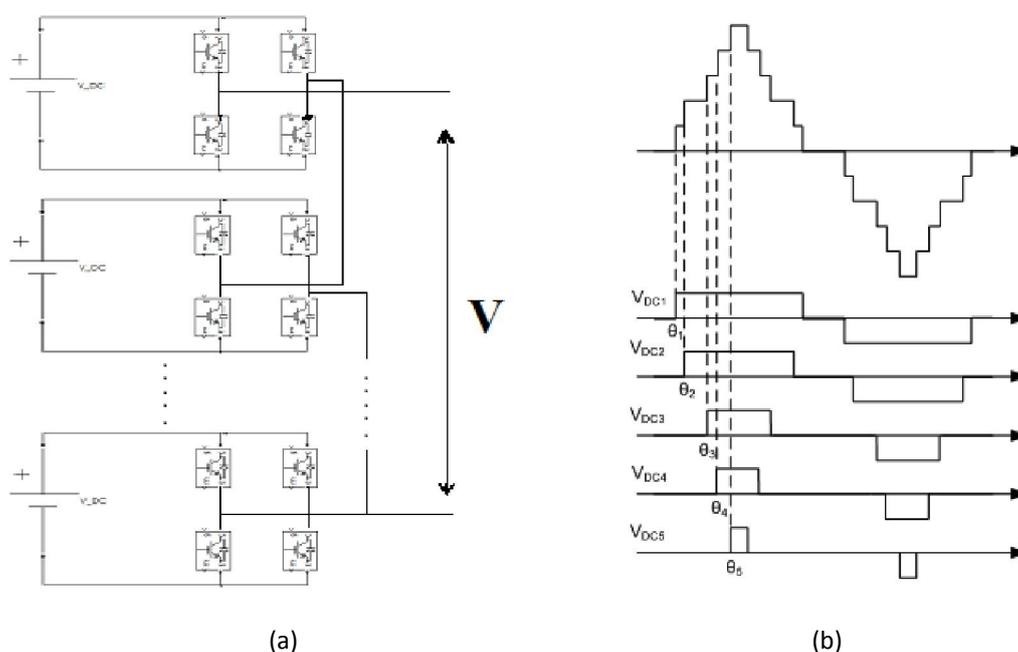


Fig. 1. (a) Structure of a single-phase cascaded multilevel inverter. (b) Staircase output voltage.

3 PROBLEM FORMULATION

Considering the equal DC source is applied to each of the inverters while taking into consideration that the characteristics of the inverter waveform Fourier series expansion of stepped output voltage waveform of the multilevel inverter with equal DC sources can be described as:

$$v_o(\omega t) = \sum_{n=1,3,5}^{\infty} \frac{4V_{dc}}{n} \{ \cos(n\theta_1) + \cos(n\theta_2) + \cos(n\theta_3) + \cos(n\theta_5) \} \times \sin(\omega t), \quad (1)$$

where V_{dc} is the nominal DC voltage and the variables $\theta_1, \theta_2, \theta_3, \theta_4, \theta_5$ (firing angles) are given as:

$$0 < \theta_1 < \theta_2 < \dots < \theta_s < \frac{\pi}{2}$$

A set of solutions is obtainable by equating $S-1$ harmonics to zero and assigning a specific value to the fundamental component, as given below. The number of harmonics which can be eliminated from the output voltage of the multilevel inverter is $S-1$. For example, to eliminate the selective harmonics for an 11-level inverter, equation set (2) must be satisfied. Note that the elimination of triple harmonics for the three-phase power system applications is not necessary, because these harmonics are automatically eliminated from the line–line voltage:

$$\begin{aligned} \cos(\theta_1) + \cos(\theta_2) + \cos(\theta_3) + \cos(\theta_4) + \cos(\theta_5) &= m \\ \cos(3\theta_1) + \cos(3\theta_2) + \cos(3\theta_3) + \cos(3\theta_4) + \cos(3\theta_5) &= 0 \\ \cos(5\theta_1) + \cos(5\theta_2) + \cos(5\theta_3) + \cos(5\theta_4) + \cos(5\theta_5) &= 0 \\ \cos(n\theta_1) + \cos(n\theta_2) + \cos(n\theta_3) + \cos(n\theta_4) + \cos(n\theta_5) &= 0 \end{aligned} \quad (2)$$

where $m = V_1 / \left(\frac{4V_{dc}}{\pi} \right)$ and the modulation index $M = m/S$. For 11 level inverter when $S=5$, then the 5th, 7th, 11th and 13th order harmonics will be eliminated. The main objective is to minimize the THD. The *objective function* to minimize the THD calculated according to the following equation:

$$F(t) = \sqrt{\sum_{n=3,5,7,\dots}^{63} (V_n)^2} / V_1 \quad (3)$$

4 THE PROPOSED OPTIMIZATION METHODS FOR THD REDUCTION

Three algorithms PSO, IPSO, and WIPSO are used to determine the optimum switching angles of H-bridge cascaded multilevel inverters for obtaining of minimum voltage THD in a wide range of modulation index. In this section, the proposed methods are described.

4.1 PARTICLE SWARM OPTIMIZATION (PSO)

PSO is an efficient optimization method that was proposed by Kennedy and Eberhart in 1995. This algorithm is a population-based stochastic optimization technique. PSO is inspired by the social behavior of creatures such as fish schooling, bird-flocking and herds of animals. In PSO, each particle in the swarm (a population of particles) is moved around in a multidimensional problem space to find the optimal point by adding a velocity with its position. According to the *gbest* model, each particle flies towards its best previous position based on its own experience and experience of nearby particles and then moves towards the best particle in the whole swarm. In this algorithm, population parameters were initialized randomly. The velocity of a particle is affected by three components; inertial momentum, social and cognitive components. The inertial component models the inertial behavior of the particle to move towards the previous direction. The social component shows the memory of the particle about the best position among the particles. The cognitive component simulates the memory of the particle about its previous best position. Each factor finds its best value so far (*pbest*) and each factor finds the best value in the group (*gbest*) between *pbests*. , Each factor tries to improve its position by using the current velocity and the distance from the *pbest* and *gbest* [16-17]. As the result, the velocity update equation is given as follows:

$$V_{i+1} = \omega \times V_i + C_1 \times r_1 \times (P_{best_i} - S_i) + C_2 \times r_2 \times (g_{best_i} - S_i) \quad (4)$$

where, V_i is current velocity of the particle, S_i is current position of the particle, ω is inertia weight, C_1 is cognition acceleration coefficient, C_2 is social acceleration coefficient, P_{best_i} is best position of particle, g_{best} is global best position among the group of particles and $r1, r2$ are uniformly distributed random numbers in the range [0 to 1].

Each particle updates its velocity and position based on (6) and (7) and tries to reach the target.

Position update equation is given as follows:

$$S_{i+1} = S_i + V_{i+1} \quad (5)$$

4.2 MODIFIED PARTICLE SWARM OPTIMIZATION (MPSO)

MPSO was proposed by Eberhart and Shi in 1997 and 1998. In this algorithm, the birds have a memory about the previous best and worst positions so that particles have 2 experiences, a bad experience helps each particle to remember its previous worst position. To calculate the new velocity, the bad experience of each particle is considered. [18]

The new velocity update equation is given as follows:

$$V_{i+1} = \omega \times V_i + C_{1g} \times r_1 \times (P_{best_i} - S_i) + C_{1b} \times r_2 \times (S_i - P_{Worst_i}) + C_2 \times r_3 \times (g_{best} - S_i), \quad (6)$$

where, C_{1g} is acceleration coefficient which accelerates the particle towards its best position, C_{1b} is acceleration coefficient which accelerates the particle away from its worst position, P_{Worst_i} is acceleration coefficient which accelerate the particle away from its worst position of the particle i , and $r1, r2, r3$ are uniformly distributed random numbers in the range [0 to 1].

4.3 WEIGHT IMPROVED PARTICLE SWARM OPTIMIZATION (WIPSO)

In the WIPSO algorithm, in order to improve the global search quality of standard PSO, the inertia weight factor and the cognitive and social components (C_1, C_2) have been configured [19]. The velocity-update equation is as follows:

$$V_{i+1} = W_{new} \times V_i + C_1 \times r_1 \times (P_{best_i} - S_i) + C_2 \times r_2 \times (g_{best} - S_i), \quad (7)$$

where

$$W_{new} = W_{min} + w \times r_1, \quad (8)$$

and w is calculated as follows:

$$w = W_{max} - [(W_{max} - W_{min}) \times ITE] / (ITE_{max}), \quad (9)$$

where, W_{max} and W_{min} are maximum and minimum inertia weight, respectively.

$$C_1 = C_{1max} - (C_{1max} - C_{1min}) \times (ITE / ITE_{max}) \quad (10)$$

$$C_2 = C_{2max} - (C_{2max} - C_{2min}) \times (ITE / ITE_{max}) \quad (11)$$

where:

C_{1min}, C_{1max} : The initial and final values of the cognitive component

C_{2min}, C_{2max} : The Initial and final values of the social component

ITE is the current iterations and ITE_{max} is the maximum of iterations.

4.4 THE PROCEDURE FOR IMPLEMENTING OF THREE STUDIED OPTIMIZATIONS TECHNIQUES

The proposed algorithms are easy to use and are computationally efficient. ϑ_i vector for an 11-level inverter is $[\vartheta_{i1}, \vartheta_{i2}, \dots, \vartheta_{i5}]$ and ϑ_i is also represented to the i^{th} particle of the swarm. The elements of ϑ_i are the solutions of the objective function, and the d^{th} element corresponds to the d^{th} switching angle of the inverter.

The procedure for implementing the three studied optimization techniques to find the optimum switching angles of an 11 level inverter is as follows:

1. First, initialize the required parameters of the algorithm such as maximum iteration number, population size M, and etc.
2. Determine the initial conditions of each particle, a population of particles are randomly initialized between 0 and $\pi/2$ and the velocity vector of each particle is randomly generated between V_{max} and V_{min} . At this point, the dimension of each particle is equal to the number of H-bridges in a cascaded multilevel inverter and also switching angles. A $2S+1$ -level inverter requires S H-bridges; thus, in an 11-level H-bridge inverter we will have 5 switching angles, $\theta_1, \theta_2, \dots, \theta_5$.
3. For each particle, the desired optimization fitness function for s variables is determined. The main purpose of this paper is to minimize specified harmonics. The cost function is given in Equation (3)
4. For updating the personal best position of the particles in the minimization process of the cost function in Equation (3), compare i^{th} particle fitness evaluation with its previous personal best position. If the current position of the i^{th} particle is better than P_{best}^i , replace P_{best}^i with the current position X^i in s-dimensional space.
5. If the personal best of the particles has the best position so far, replace the present personal best, which is called the global best with the previous one.
6. Update the velocity and position of the particle by equations (4) and (5) and repeat the optimization process to get the desired solution.
7. If the iteration counter reaches the ITE_{max} , stop the process to find the final result; else, increase the iteration counter and repeat the process from step (3).

For applied WIPSO and MPSO algorithms in the optimization process, go back to step 6 and replace the Equation (6) for MPSO and Equations (7-11) for WIPSO with Equation (4) and (5) then continue the procedure.

5 SIMULATION RESULTS AND DISCUSSIONS

In order to evaluate the accuracy and performance of the proposed methods, a single phase 11-level cascaded H-bridge inverter is considered to optimize switching angles $\theta_1, \theta_2, \theta_3, \theta_4, \theta_5$ by simulating in MATLAB/SIMULINK software. The SHE problem is solved by using PSO, MPSO and WIPSO algorithms to minimize THD. The switching angles for the three proposed (PSO, MPSO, WIPSO) algorithms are shown in Figs. 2-4, respectively.

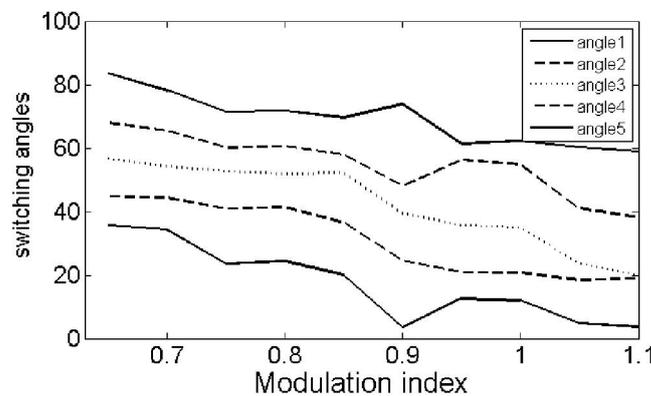


Fig. 2. Optimum switching angles versus M with PSO algorithm

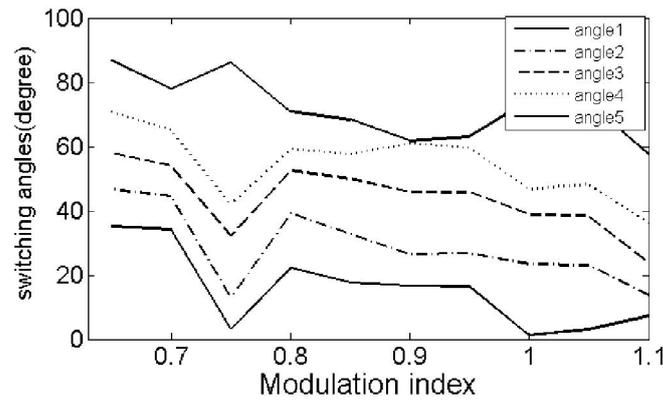


Fig. 3. Solutions for switching angles versus M with MPSO algorithm

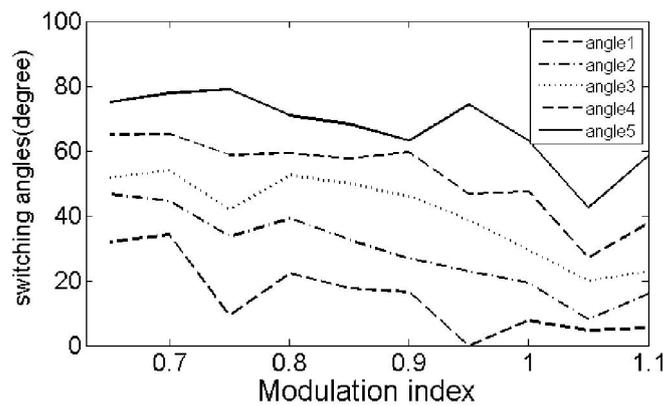


Fig. 4. Solutions for switching angles versus M with WIPSO algorithm

Figs. 5-6 show the THD and objective function versus the modulation index (M), respectively. Figure 5 represents the performance of the three mentioned algorithms for THD reduction which depends on amplitude modulation index (M). As shown in this figure, MPSO has a lower THD than PSO and WIPSO for low modulation index (about below 0.8), whereas, for modulation about 1 and more, the WIPSO has a lower THD, and for other ranges of modulation index, PSO has the lower THD among three proposed methods.

Figure 6 shows that MPSO and WIPSO algorithms have iteration numbers lower than the PSO algorithm. The PSO algorithm converged at the 80th iteration while the MPSO and WIPSO converged at the 33th and 28th iteration, respectively. Also, the WIPSO algorithm has higher convergence speed among the proposed methods.

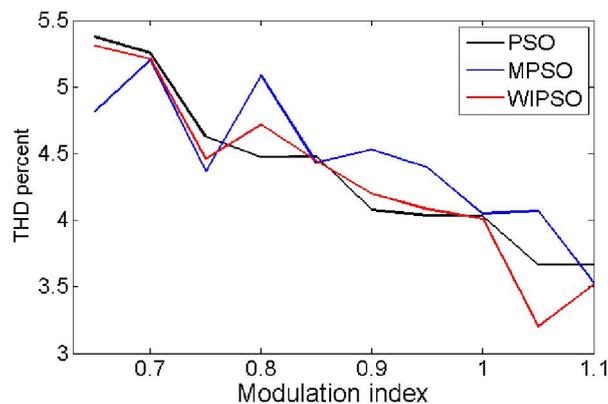


Fig. 5. Corresponding THD values versus M

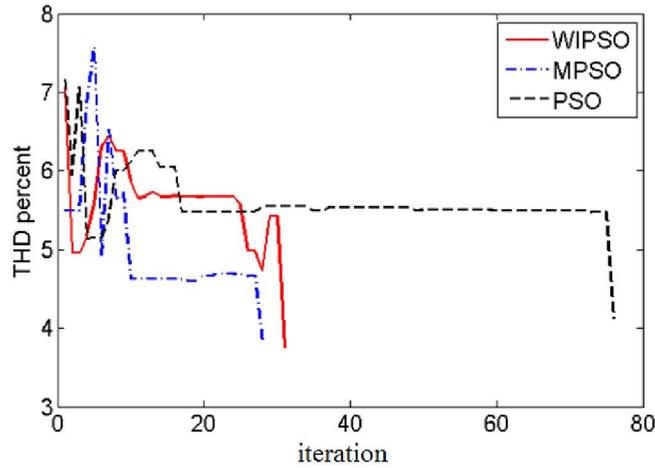


Fig. 6. Comparison of Corresponding THD values for PSO, MPSO and WIPSO versus iteration

Figure 7 shows the rate of objective function for the three mentioned algorithms. The objective function to eliminate the 5th, 7th, 11th and 13th order harmonics for an eleven level inverter is given by equation (3). Figure 7 also shows that WIPSO algorithm has a higher convergence speed among the proposed algorithms.

Fast Fourier Transformer (FFT) analysis of the 11-level cascaded inverter is presented in Figs. 8-12, for the three studied algorithms using modulation index of 0.7, 0.8, 0.9, 1, and 1.1, respectively.

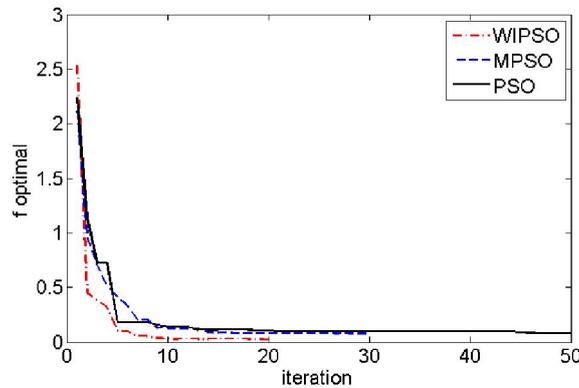


Fig. 7. Comparison of objective function for PSO, MPSO and WIPSO versus iteration

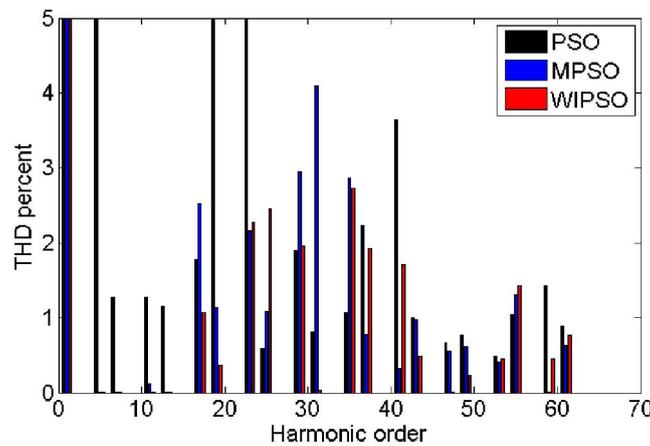


Fig. 8. FFT analysis of the 11 level cascaded inverter with PSO, MPSO and WIPSO algorithms (for modulation index of 0.7)

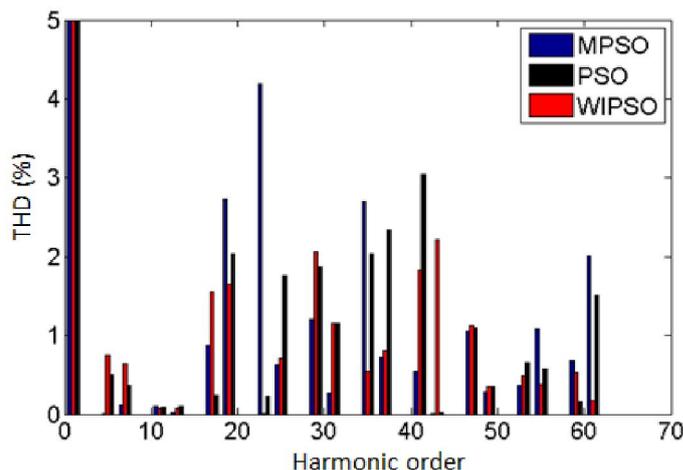


Fig. 9. FFT analysis of the 11 level cascaded inverter with PSO, MPSO and WIPSO algorithms (for modulation index of 0.8)

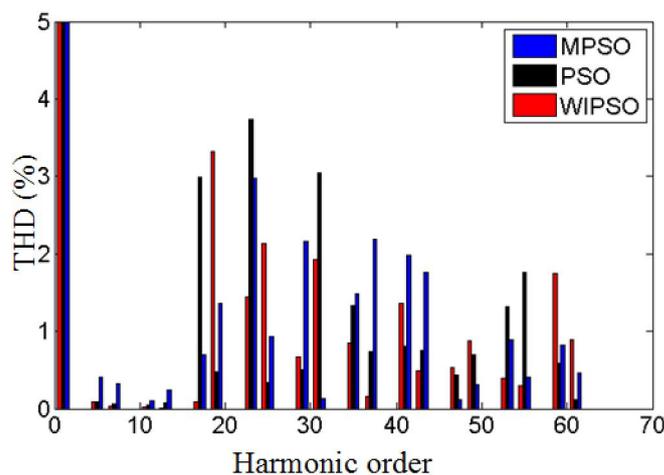


Fig. 10. FFT analysis of the 11 level cascaded inverter with PSO, MPSO and WIPSO algorithms (for modulation index of 0.9)

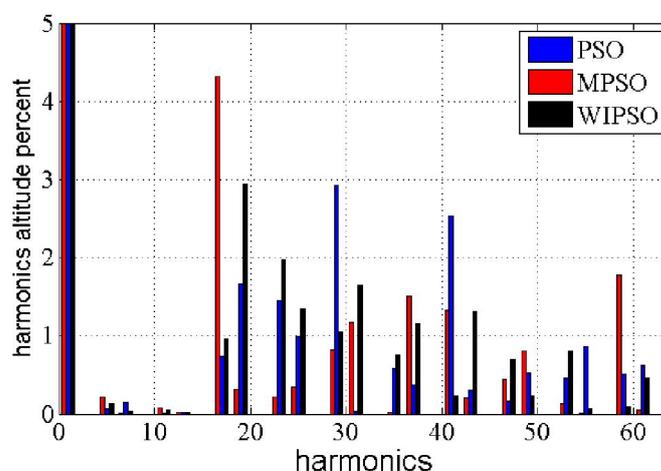


Fig. 11. FFT analysis of the 11 level cascaded inverter with PSO, MPSO and WIPSO algorithms (for modulation index of 1)

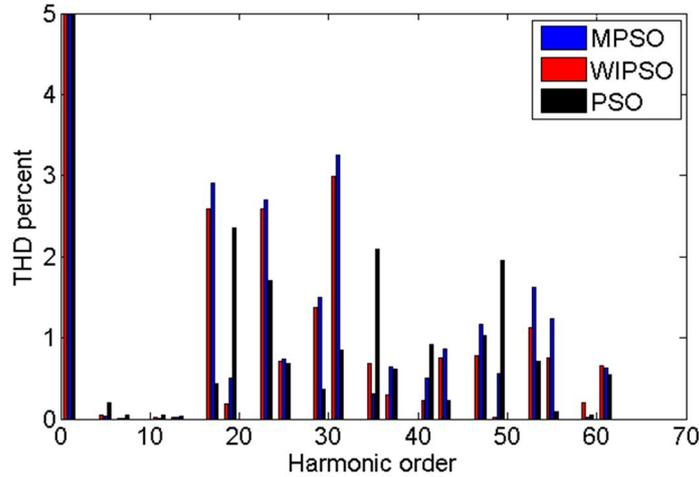


Fig. 12. FFT analysis of the 11 level cascaded inverter with PSO, MPSO and WIPSO algorithms (for modulation index of 1.1)

Tables 1 to 5 show the ratio of harmonic component amplitude to fundamental component amplitude in percent for the three algorithms (PSO, MPSO and WIPSO) in different harmonic orders for the 11-level inverter with modulation index of 0.7, 0.8, 0.9, 1, and 1.1, respectively.

Table 6 presents the comparison of switching angles and THD percent for the three algorithms (PSO, MPSO and WIPSO) in different modulation index for 11 levels inverter. As shown in this Table, MPSO has the lower THD than PSO and WIPSO for low modulation index (below 0.8), where for modulation about 1 and more than this, the WIPSO has lower THD, and for the other range of modulation index, PSO has the lower THD among the three proposed methods. Table 6 shows that the MPSO algorithm has the smallest THD percent in comparison with the two other algorithms with modulation index 0.7. The WIPSO algorithm with modulation index 1 and 1.1 results in the THD percent of 4.01 and 3.52, respectively, which has a smaller amount in comparison to the other two algorithms. Finally, THD percent is 4.47 and 4.07 in PSO algorithm with modulation index 0.8 and 0.9, respectively, which has the smallest amount among three mentioned algorithms.

Table 1. Comparison of the ratio of harmonic component amplitude to fundamental component amplitude in percent for three algorithms (PSO, MPSO & WIPSO) in different harmonic order for the 11-level inverter (with modulation index of 0.7)

Harmonic order	5	7	11	13
harmonics amplitude percent with PSO	6.59	1.28	1.27	1.159
harmonics amplitude percent with MPSO	0.145	0.013	0.0134	0.018
harmonics amplitude percent with WIPSO	0.0031	0.0589	0.0946	0.086

Table 2. Comparison of the ratio of harmonic component amplitude to fundamental component amplitude in percent for three algorithms (PSO, MPSO & WIPSO) in different harmonic order for 11 levels inverter (with modulation index of 0.8)

Harmonic order	5	7	11	13
harmonics altitude percent with PSO	0.49	0.37	0.086	0.099
harmonics altitude percent with MPSO	0.01	0.111	0.1	0.020
harmonics altitude percent with WIPSO	0.754	0.63	0.079	0.082

Table 3. Comparison of the ratio of harmonic component amplitude to fundamental component amplitude in percent for three algorithms (PSO, MPSO & WIPSO) in different harmonic order for 11 levels inverter (with modulation index of 0.9)

Harmonic order	5	7	11	13
harmonics altitude percent with PSO	0.09	0.06	0.04	0.07
harmonics altitude percent with MPSO	0.4	0.32	0.1	0.23
harmonics altitude percent with WIPSO	0.093	0.037	0.0139	0.007

Table 4. Comparison of the ratio of harmonic component amplitude to fundamental component amplitude in percent for three algorithms (PSO, MPSO & WIPSO) in different harmonic order for 11 levels inverter (with modulation index of 1)

Harmonic order	5	7	11	13
harmonics altitude percent with PSO	0.06452	0.1505	0.0031	0.0146
harmonics altitude percent with MPSO	0.211	0.0104	0.0716	0.0258
harmonics altitude percent with WIPSO	0.1264	0.0340	0.0424	0.0189

Table 5. Comparison of the ratio of harmonic component amplitude to fundamental component amplitude in percent for three algorithms (PSO, MPSO & WIPSO) in different harmonic order for 11 levels inverter (with modulation index of 1.1)

Harmonic order	5	7	11	13
harmonics altitude percent with PSO	0.196	0.049	0.054	0.034
harmonics altitude percent with MPSO	0.04	0.00018	0.009	0.016
harmonics altitude percent with WIPSO	0.049	0.00002	0.017	0.021

Table 6. Comparison of switching angels and THD percent for three algorithms (PSO, MPSO & WIPSO) in different modulation index for 11-level inverter

M		0.7	0.8	0.9	1	1.1
θ_1	PSO	34.52	24.4	3.60	12.0	3.81
	MPSO	34.35	22.35	16.7	1.43	7.46
	WIPSO	34.38	22.34	16.7	7.86	5.54
θ_2	PSO	44.45	41.54	24.63	20.86	19.03
	MPSO	44.659	39.304	26.572	23.568	13.648
	WIPSO	44.64	39.29	26.99	19.38	16.18
θ_3	PSO	54.315	52.091	39.549	35.180	20.065
	MPSO	54.14	52.71	45.93	38.88	23.99
	WIPSO	54.17	52.71	46.10	29.66	23.00
θ_4	PSO	65.598	60.732	48.105	54.999	38.252
	MPSO	65.399	59.35	61.104	46.832	36.512
	WIPSO	65.40	59.34	59.71	47.70	37.91
θ_5	PSO	78.24	71.88	74.01	62.35	59.08
	MPSO	77.91	71.00	61.89	74.68	57.63
	WIPSO	77.95	70.99	63.43	63.24	58.72
THD in percent	PSO	5.26	4.47	4.07	4.03	3.67
	MPSO	5.206	5.089	4.532	4.051	3.534
	WIPSO	5.21	4.72	4.20	4.01	3.52

6 CONCLUSION

The main purpose of this paper was to eliminate the selective harmonic in H-bridge cascaded multilevel inverters with equal source to reduce the total harmonic distortion (THD). In order to achieve this purpose, three algorithms PSO, MPSO and WIPSO were applied to determine optimum switching angles of converter switches. The main conclusions of this paper were drawn as follows:

- The performance of the three proposed algorithms for THD reduction depends on amplitude modulation index (M)
- MPSO has the lower THD than PSO and WIPSO for low modulation index (below 0.8), whereas, for modulation about 1 and more, the WIPSO has lower THD, and for other ranges of modulation index, PSO has the lower THD among three proposed methods.
- MPSO and WIPSO algorithms achieve lower iteration numbers compared to the PSO algorithm. Also, the WIPSO algorithm has the highest convergence speed among the proposed methods.
- All three proposed algorithms reduce the 5th, 7th, 11th and 13th order harmonics in the optimization problem.

- The WIPSO algorithm finds the answer with less iteration and it has higher convergence speed among the proposed methods.

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