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MODIFIED QUANTUM PARTICLE SWARM OPTIMIZATION FOR SELECTIVE HARMONIC ELIMINATION (SHE) IN A SINGLE-PHASE MULTILEVEL INVERTER

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Abstract. *The Multilevel Inverter (MLI) uses Selective Harmonic Elimination (SHE) of the Pulse Width Modulation (PWM) approach to tackle the fundamental harmonics with the elimination of selected lower harmonics. The optimal switching angle for this PWM method is calculated by solving a set of nonlinear equations. The PWM signal is generated using these angles in a real-time system. Modified Quantum Particle Swarm Optimization (MQPSO) is implemented in this paper to provide the optimal angle for generating the PWM signal. In this study, 5 optimal switching angles for a single-phase 11-level MLI have been calculated. It is observed that MQPSO produces optimal switching for modulation indices between 0.4 and 0.7. To obtain a quarter-wave symmetry bipolar waveform output voltage, the MQPSO based SHE-PWM has been developed and implemented by using MATLAB Simulink. The output voltage and harmonic spectrum of the proposed system are also obtained using MATLAB. Furthermore, the results are also compared with another modulation technique to validate the superiority of MQPSO based SHE-PWM. The Total Harmonic Distance (THD) has been reduced by 3.62% compared to Nearest Level Control (NLC), which has verified that the proposed method has successfully eliminated the low-order harmonics.*

Keywords: Modified quantum behaved particle swarm optimization algorithm, Selective harmonic elimination, Multilevel inverters

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1. **Introduction.** Domestically and industrially pulse width modulated VSI is very popular for different applications. This type of inverter produces an output voltage waveform which is typically square/quasi-square in nature but involves various types of harmonics that are not suitable for application in a high power system. With low switching frequency, SHE is used as a PWM technique to handle fundamental harmonics. It is also used to remove unexpected lower order harmonics which generate from the inverter's voltage waveform. Later, with the help of a small passive filter the residuary harmonics are removed which are of a higher order. Hence, the grid's harmonic distortion is eventually decreased. Again, there is a necessity of high-speed digital signal processing tools for the execution of SHE-PWM algorithms. Nowadays the development of SHE-PWM is achieving a new interest from the researcher because it has some advantages [1-4]. It can gain a higher voltage with higher modulation. It can reduce switching losses and reduce the DC-link voltage's ripple. Besides, it can remove lower order harmonics [5]. During the digital process, it follows two steps. One is switching angle determination and the other one is analyzing data from stored memory. At first, by solving the nonlinear transcendental equation it determines N number of switching angles with respect to different modulation indexes. These equations are formulated as a function of switching angles. By using the Fourier transform of the voltage waveform, these equations are achieved [6]. Previous studies indicated that several methods like Particle Swarm Optimization (PSO), Genetic Algorithm (GA), Walsh functions, and Newton-Raphson were used to solve these specific equations. In the case of the Newton-Raphson method, the selection of the switching angle's initial value plays an important role in convergence. Since initial values vary with respect to the problem, it cannot be determined by a fixed formula [7]. Fourier Walsh conversion matrix was used for converting the transcendental equation set to linear equations in the case of Walsh functions [8,9]. After conversion, it started its optimization [10]. PSO was also used to solve this nonlinear optimization problem [11]. By nature, PSO is an evolutionary algorithm that mimics the food searching technique of birds flock [12,13]. Another most popular algorithm GA was also used to solve this problem. Because of their ability to determine optimal switching angles with high precision, both evolutionary algorithms were effective to eliminate lower order harmonics. Among these algorithms, PSO performs better than GA because of its easier application, less computational time and better THD minimization [14]. In case of GA it needs to adjust the mutation operator and crossover operator during optimization. Otherwise it may fall into local optima trap. In original PSO, trial and error method was used to set the value for acceleration coefficients. Original PSO also has a problem of premature convergence. Later to eliminate this time-consuming complexity for fine tuning, different modified PSO algorithms were proposed. There local search was incorporated with PSO [15]. Another concern regarding PSO is, if the number of switching angles becomes more conventional PSO needs a long search table to store the data which will be difficult for a digital signal processor to find all the optimum solutions. It will miss some significant optimal operating points. To overcome this issue, in recent studies, DE [16-18], FF [19], and BA [20] are used to find the optimal solution. However, no algorithm is appropriate to all sorts of problems, according to the No Free Lunch theorem (NFL) [21]. Since metaheuristic techniques provide an optimal solution, it can be improved with the incorporation of other techniques for certain optimization problem and usually provides the best results in terms of selective harmonic eliminations. The practical significance of selective harmonic elimination in a single-phase multilevel inverter is given below:

- Smaller filtering requirements.
- Elimination of low-order harmonics, results in no harmonic interference which can be employed in inverter power supplies.

- Performance indicators can also be optimized for different quality aspects, such as Total Harmonic Distortion (THD).
- Wide converter bandwidth and high voltage gain.

To remove the selected 4 low-order odd harmonics (5th, 7th, 11th, and 13th) and control fundamental harmonic from the output voltage waveform of single-phase 11-level Cascaded H-Bridge (CHB) MLI, a Modified Quantum Particle Swarm Optimization (MQPSO) based SHE-PWM algorithm is proposed in this study. In this study, MQPSO is demonstrated to obtain optimum switching angles through the variable modulation indexes. These switching angles have been used to generate PWM signals for the non-identical frequencies [22]. Results analysis of the proposed algorithm is accomplished by using MATLAB Simulink. After that, the output voltage of the CHB MLI is measured and the harmonic spectrum is used to analyze the harmonics of the output voltage of the inverter.

This paper has been structured as below. In Section 2 the fourth wave symmetry has been formed with a line-to-neutral waveform of a SHE-PWM inverter. In Section 3, the transcendental equations have been optimized to determine the switching angles with the use of MQPSO. In Section 3, MQPSO has been used to evaluate the optimum angle and produce PWM signals. In Section 4, the inverter voltage harmonics have been calculated experimentally, and the results have been addressed. The findings have been discussed in Section 5.

Nomenclature.

Acronyms

CHB	Cascade H-Bridge
GA	Genetic Algorithm
THD	Total Harmonic Distortion
PSO	Particle Swarm Optimization
MQPSO	Modified Quantum Particle Swarm Optimization
MLI	Multilevel Inverter
QPSO	Quantum Particle Swarm Optimization
SHE	Selective Harmonic Elimination
PWM	Pulse Width Modulation
NLC	Nearest Level Control
NFL	No Free Lunch

Symbols

$j(0, \sigma^2)$	A Gaussian distribution
$Rand$	Random
d	Dimension
w	Inertia weight
m	Modulation index

Greek Symbols

β	The contraction expansion coefficient
α	Switching angles

Subscripts

min	Minimum
max	Maximum

2. **Problem Formulation.** In this work Selective Harmonic Elimination (SHE) modulation technique is used to produce the switching pulses for a single-phase Cascaded

H-Bridge (CHB) multilevel inverter having the ability to produce an 11-level output voltage. The schematic diagram of the CHB MLI is shown in Figure 1 including the current paths for the positive voltage cycle. Moreover, in the negative voltage cycle, the current paths will be reversed. This configuration consists of 5 individual CHB modules connected with each other in a cascaded configuration. Each of these CHB modules has 4 switches and 1 DC supply, making a total of 20 switches and 5 DC supplies. All the DC supplies are equal in magnitude, making it a symmetrical configuration. It can be observed from the current path that each module of CHB is utilized for generating 2 voltage levels (one in the positive half cycle and the other in the negative half cycle). The output load is connected with the CHB MLI between points A and B as shown in Figure 1. It can be noticed that the entire configuration is composed of 5 CHB cells. Furthermore, each CHB cell is contributing to producing 2 voltage levels throughout the entire operation or one voltage level in each voltage cycle. The combination of all the CHB cells is generating the 11-level desired voltage output.

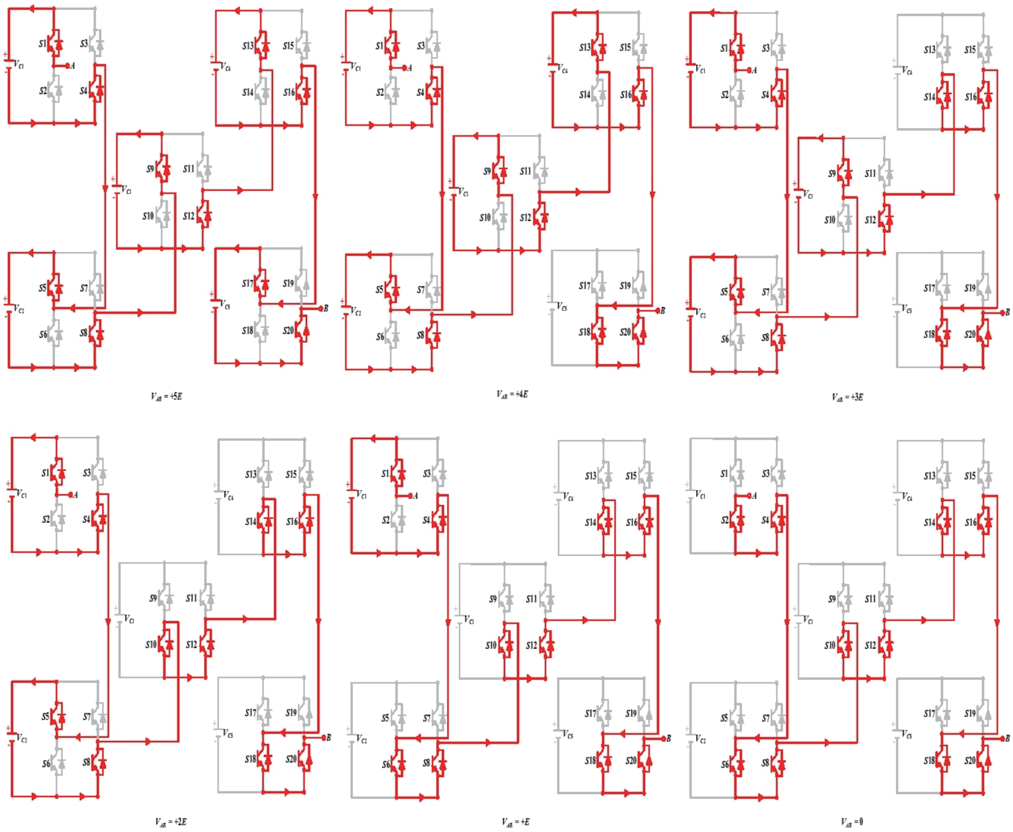

FIGURE 1. Configuration and current paths of an 11-level single-phase CHB MLI for positive voltage cycle

Generally, this modulation technique is conducted by decoding the PWM waveform utilizing Fourier-analysis. Fourier series of a periodic function is represented by the following equation:

$$f(t) = a_0 + \sum_{r=1}^{\infty} a_r \cos(r\omega t) + b_r \sin(r\omega t). \tag{1}$$

In this case, $f(t) =$ odd and as a result (1) can be written as follows:

$$f(t) = \sum_{r=1}^{\infty} b_r \sin(r\omega t). \tag{2}$$

Here, b_r can be determined by

$$b_r = \frac{4E}{r\pi} \sum_{i=1}^{i} \cos(r\alpha_i). \tag{3}$$

Since the triple harmonics usually get eliminated in three-phase systems, these harmonic components are neglected. Thus, 5th, 7th, 11th, and 13th harmonic components were eliminated from the output voltage of the CHB inverter. A nonlinear set of equations is used to eliminate the specific harmonics from the output voltage. This nonlinear equation set is achieved from (4) by equating $b_3, b_5, b_7, b_{11}, b_{13}$ to zero as follows:

$$\begin{aligned}
b_1 &= \frac{4E}{\pi}[\cos(\alpha_1) + \cos(\alpha_2) + \cos(\alpha_3) + \cos(\alpha_4) + \cos(\alpha_5)] = m, \\
b_3 &= \frac{4E}{3\pi}[\cos(3\alpha_1) + \cos(3\alpha_2) + \cos(3\alpha_3) + \cos(3\alpha_4) + \cos(3\alpha_5)] = 0, \\
b_5 &= \frac{4E}{5\pi}[\cos(5\alpha_1) + \cos(5\alpha_2) + \cos(5\alpha_3) + \cos(5\alpha_4) + \cos(5\alpha_5)] = 0, \\
b_7 &= \frac{4E}{7\pi}[\cos(7\alpha_1) + \cos(7\alpha_2) + \cos(7\alpha_3) + \cos(7\alpha_4) + \cos(7\alpha_5)] = 0, \\
b_{11} &= \frac{4E}{11\pi}[\cos(11\alpha_1) + \cos(11\alpha_2) + \cos(11\alpha_3) + \cos(11\alpha_4) + \cos(11\alpha_5)] = 0, \\
b_{13} &= \frac{4E}{13\pi}[\cos(13\alpha_1) + \cos(13\alpha_2) + \cos(13\alpha_3) + \cos(13\alpha_4) + \cos(13\alpha_5)] = 0.
\end{aligned} \tag{4}$$

To eliminate the selected harmonic components, (4) must be solved in such a way that the condition of $\left(0 \le \alpha_1 \le \alpha_2 \le \alpha_3 \le \alpha_4 \le \alpha_5 \le \frac{\pi}{2}\right)$ is satisfied, where α_1, α_2, α_3, α_4, α_5 represent switching angles. It is worth noting that the 1st switching angle α_1 is used to control the fundamental component of the voltage output while all other switching angles $(\alpha_2, \alpha_3, \alpha_4, \alpha_5)$ are used to eliminate the predefined harmonic components. These switching angles are calculated by solving an objective function using MQPSO algorithm and derived from (4). The objective and its constraints functions are derived as follows:

$$\text{Min } F(\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5) \tag{5}$$

$$\begin{aligned}
F(\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5) = {} & \left[\left(\sum_{i=1}^{5} \cos\alpha_i - 5m\right)^2 + \left(\frac{4}{5\pi}\sum_{i=1}^{5}\cos(5\alpha_i)\right)^2\right. \\
& + \left(\frac{4}{7\pi}\sum_{i=1}^{5}\cos(7\alpha_i)\right)^2 + \left(\frac{4}{11\pi}\sum_{i=1}^{5}\cos(11\alpha_i)\right)^2 \\
& \left. + \left(\frac{4}{13\pi}\sum_{i=1}^{5}\cos(13\alpha_i)\right)^2\right].
\end{aligned} \tag{6}$$

Here, F represents the fitness value.

Figure 2 illustrates the staircase output voltage of the 11-level CHB MLI for the positive voltage cycle. It can be observed that each edge of each stair is representing one switching angle. These switching angles are the key to eliminate selective harmonics. The first switching angle denoted by α_1 represents the fundamental voltage components whereas the other angles (α_2 to α_5) are used to remove the harmonics. By utilizing the correct switching angles determined by a particular optimization algorithm, selective harmonics can be removed entirely. In this manuscript, the selection of accurate switching angles (α_i) is done by applying MQPSO method which will be discussed in the next section.

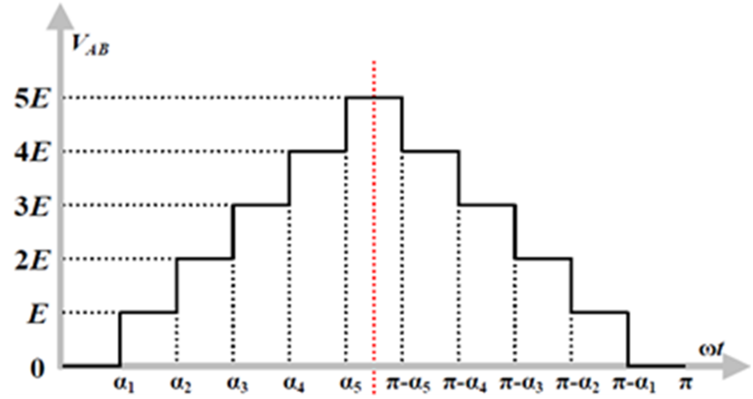

FIGURE 2. Staircase output voltage waveform of 11-level single-phase CHB MLI

3. **Methodology.** The Ross study found that quantum behaved algorithms are better than current metaheuristic algorithms for optimization applications [23,24]. Another research showed that the quantum technique would handle extremely non-linear problems of optimization [23,25]. One main difference is PSO searches linearly and QPSO, on the other hand, is entirely based on the probabilistic approach [26].

In 1995, a novel search approach was developed and proposed by Kennedy and Eberhart [12], which is known as PSO. In PSO, the initialization of individuals is done through a random process.

To update the velocity of each particle, the following equation is utilized

$$V_i^{k+1} = wV_i^k + c_1 rand_1 \left(pbest_i^k - x_i^k\right) + c_2 rand_2 \left(gbest^k - x_i^k\right), \tag{7}$$

here the individual i particle's velocity is denoted by V_i for iteration k; c_1 and c_2 are acceleration constants; w is used for weight vector; $rand_1$ and $rand_2$ are the random numbers ranging from 0 to 1; in iteration k, x_i^k represents the position of individual i, $pbest_i^k$ and $gbest^k$ denote the best positions of individual i. In the search space, each particle's next position will be updated using Equation (8)

$$x_i^{k+1} = V_i^{k+1} + x_i^k. \tag{8}$$

To provide better solutions and remove the drawbacks of PSO, Sun et al. proposed an algorithm named as the QPSO algorithm in their research [27].

The QPSO algorithm not only solves the shortcomings of the PSO algorithm [28] but also can be combined with an improved search technique for faster convergence [29]. Figure 3 presents the MQPSO flowchart. At first, initially, the positions are randomly generated. Then the fitness function for each particle is calculated. Depending on the result, contraction expansion, *mbest* and *gbest* are updated. The search process continues until the exit criteria are met.

In D dimensional quantum space, with a population consisting of k-particles, the best particle position, i.e., *gbest*, can be presented as $Q_g = (Q_{g1}, Q_{g2}, \ldots, Q_{gD})$ in the search space. The position of the ith particle can now be determined by $X_i = (x_{i1}, x_{i2}, \ldots, x_{iD})$. Similarly, *pbest* can be presented as $Q_i = (Q_{i1}, Q_{i2}, \ldots, Q_{iD})$ for the ith particle's best solution. Hence, the quantum position of the particle can be represented as using the Monte-Carlo process given below [28]:

$$x_{id} = q_{id} \pm \frac{L}{2} \ln\left(\frac{1}{u}\right), \tag{9}$$

here dimension $d = 1, 2, \ldots, D$; u is random number between $[0, 1]$; $i = 1, 2, \ldots, n$; in d dimension local attractor of the ith particle is denoted q_{id} and written as [30]:

$$q_{id} = \varphi \cdot Q_{id} + (1 - \varphi) \cdot Q_{gd}, \tag{10}$$

where φ is known as a random number $[0, 1]$.

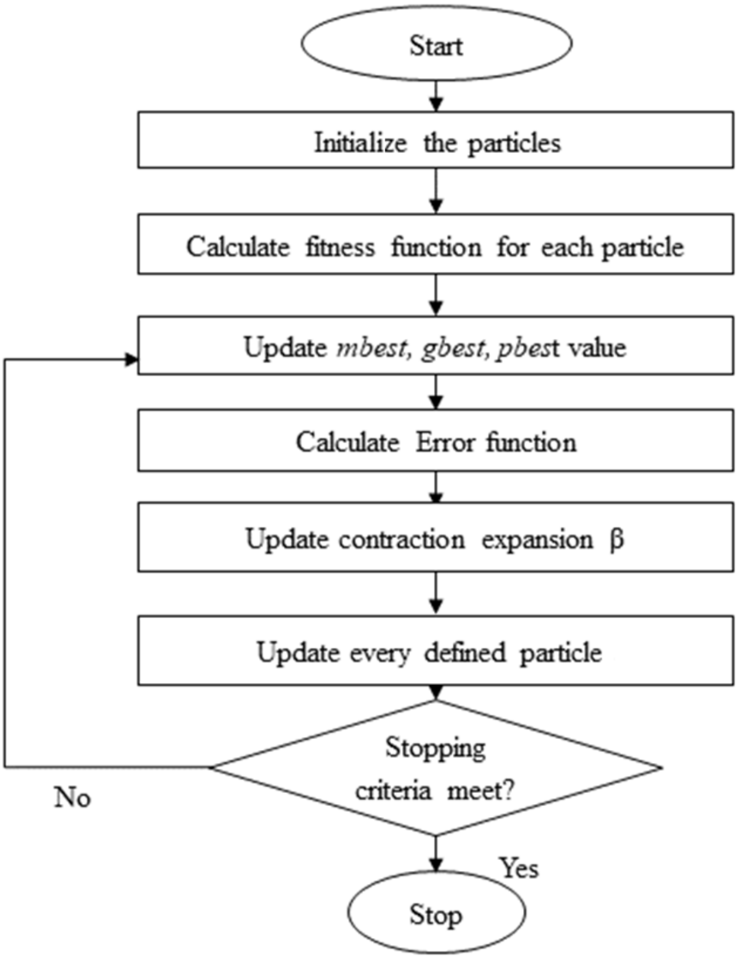

FIGURE 3. Flowchart of modified quantum particle swarm optimization

A numerical number, L, came from an individual's current and best location, which is represented as $L = 2 \cdot \beta|q_{id} - x_{id}|$. The quantum state of the location of the particle is now represented as Equation (11):

$$x_{id} = q_{id} \pm \beta|q_{id} - x_{id}| \ln\left(\frac{1}{u}\right), \tag{11}$$

here, Contraction Expansion (CE) is defined as β, the only above mentioned QPSO parameter earlier.

An adaptive CE parameter management approach for improved parameter control is addressed in order to utilize the adaptive process. First of all, the following error function is added:

$$\Delta F = \frac{F_i - F_{gbest}}{Min(abs(F_i), abs(F_{gbest}))}, \tag{12}$$

where the minimum value between X_1 and X_2 is given in $Min(X_1, X_2)$. The global fitness value is F_{gbest}, the fitness value ith particle is F_i and the absolute value is depicted by abs function.

Now, let $k = \log \Delta F$, and then the function is

$$\beta(k) = \begin{cases} 0.6 & k > 0 \\ 0.7 & -2 < k \leq 0 \\ 0.6 + 0.1 * z & -z - 1 < k \leq -z \ (z = 2, 3, 4) \\ 1 + 0.2 * (z - 4) & -z - 1 < k \leq -z \ (z = 5, 6, 7) \\ 1.8 & k \leq -8 \end{cases}. \tag{13}$$

The value of β is changed from 1 to 0.5 in each run [30]. Based on the error function β value is selected from 0.6 to 1.8. If difference between global best and fitness value is large, small value of β is assigned. Hence, $|mbest_d - x_{id}|$ is given less weight. If difference between global best and fitness value is small, large value of β is assigned for faster convergence.

Premature convergence is a common problem in the traditional PSO algorithm. To address this issue, *mbest* is proposed in QPSO by Sun et al. [27]. The *mbest* can be described as

$$mbest = \frac{1}{k} \sum_{i}^{k} Q_i = \left[\frac{1}{k} \sum_{i=1}^{k} Q_{i1}, \frac{1}{k} \sum_{i=1}^{k} Q_{i2}, \ldots, \frac{1}{k} \sum_{i=1}^{k} Q_{iD} \right]. \tag{14}$$

The best possible location in this particle i's is suggested by Q_i. Hence, Equation (14) will be changed as the following when *mbest* is used:

$$x_{id} = q_{id} \pm \beta |mbest_d - x_{id}| \ln \left(\frac{1}{u} \right). \tag{15}$$

4. **Results.** The maximum number of iterations and swarms in each experiment is 500 and 25, respectively. At first, in MQPSO, the switching angles are randomly initialized. At each iteration, MQPSO's search equation is used to update the switching angle variables and update the fitness value. The algorithm considers values of m from 0.1 to 1 with 0.001 intervals. For a particular value of m, the algorithm finds and stores the smallest fitness value. The variable corresponding to the minimum fitness value is the switching angle $(\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5)$. The parameters that are used for this algorithm to solve this problem, are listed in Table 1. In Table 1 acceleration coefficient (c_1 and c_2) and inertia weight (w) are listed. In the simulation, the algorithm performs best if the velocity equation with acceleration coefficient (c_1 and c_2) is updated with 1.494 and inertia weight is updated from 1 and 0.5, respectively [25].

Table 1. Parameters used for the MQPSO algorithm [25]

Algorithm	**Parameter configuration**	
	Parameter name	**Value**
MQPSO	Acceleration coefficient c_1 and c_2	1.494
	Initial inertia weight, $w_{\max}$	1
	Final inertia weight, $w_{\min}$	0.5

Figure 4 illustrates the different switching angles for different modulation indexes (m) using MQPSO algorithm.

Figure 5 has shown the progress of fitness value with respect to the modulation index. The switching angles at $m = 0.7$ have been shown in Table 2. It is observed that the MQPSO based SHE technique has given the optimum fitness values when modulation indexes remain within $0.4 \leq m \leq 0.9$ range. And it has shown a tendency to increase after $m = 0.9$. However, the fitness value has started to converge when the modulation index becomes 0.3. It has fully converged after it crossed the $m = 0.4$ value. The convergence

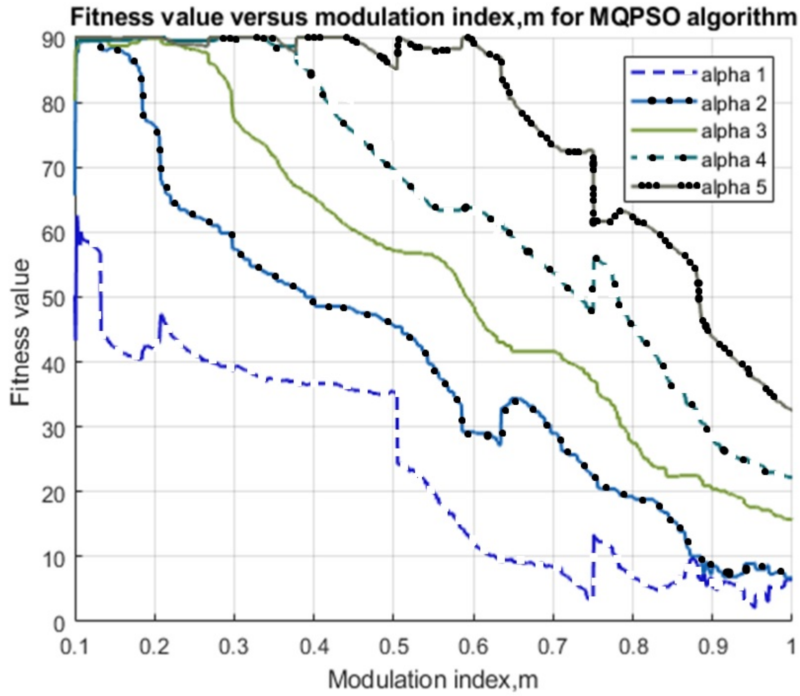

FIGURE 4. Calculated switching angles ($\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5$) at a different range of m using the MQPSO algorithm

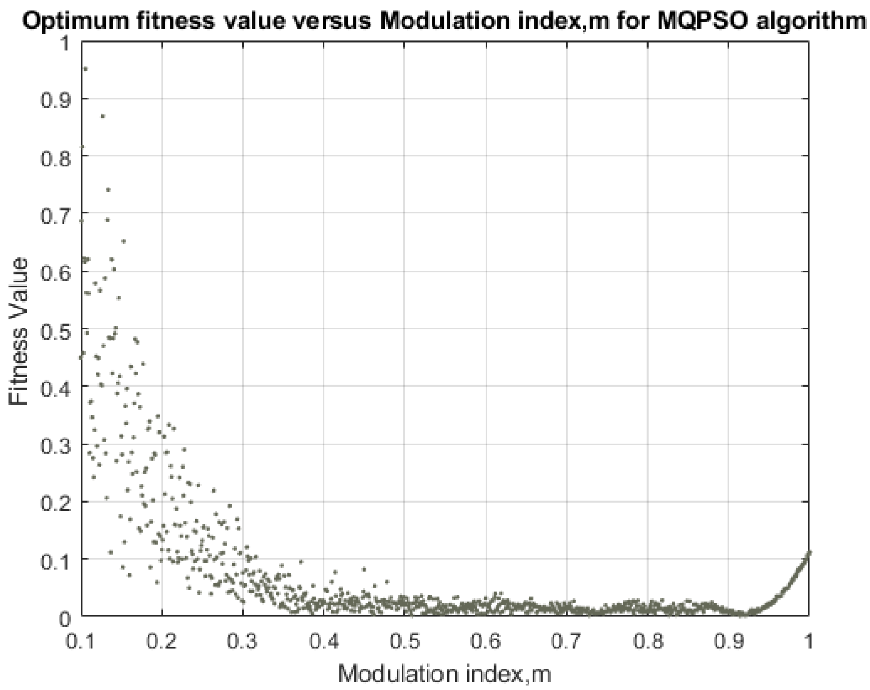

FIGURE 5. Fitness value vs modulation index curve

curve of fitness value (when $m = 0.7$) with the progress of iteration has been depicted in Figure 6. From the curve, it is found that the fitness value gradually decreased to 100 iterations. After that its value has been sharply decreased from 0.5 to 0.18. It is due to the significant exploitation capability of MQPSO. Due to this capability, MQPSO has taken less iteration to converge.

TABLE 2. Switching angles at $m = 0.7$

Nomenclature	α_1	α_2	α_3	α_4	α_5
Values	8.306	28.814	41.368	53.558	73.453

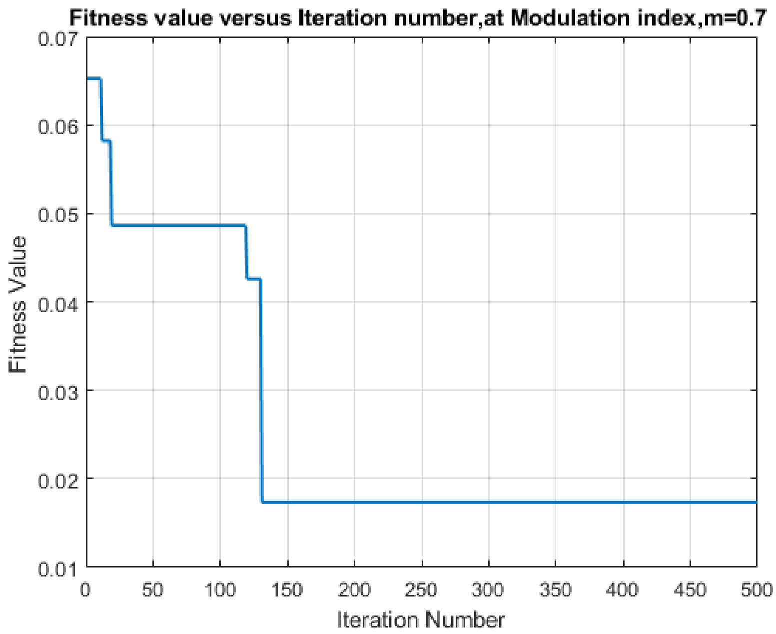

FIGURE 6. Fitness value vs iteration number curve

This section has validated the simulation results of the SHE-PWM for the CHB MLI tested. In MATLAB Simulink the 11 level CHB MLI was modeled to be of a fundamental frequency $f = 50$ Hz, and the supply was connected with 5 symmetric DC voltage sources of $E1 = 100$ V. In addition, a single-phase resistive inductive load with $R = 227$ Ω, $L = 0.536$ H was connected with output in series. The harmonic spectrum derived from SHE-PWM is contrasted with the results for the same inverter in a similar low-frequency approach. Nearest Level Control (NLC) technique is implemented in this regard [29-32]. The contrast is made with the ($m = 0.7$) same modulation index since the MQPSO algorithm only has $0.4 \leq m \leq 0.9$ solutions. Note that SHE-PWM does not provide solutions for all modulation index ranges. This is a big limitation of the SHE-PWM, discussed in depth in [33]. The output voltage waveform of the CHB MLI using both MQPSO based SHE-PWM and NLC technique at $m = 0.8$ is depicted in Figure 7(a) and Figure 7(b) respectively whereas the harmonic spectrums are shown in Figure 8 consecutively. It can be observed from comparing Figure 8(a) and Figure 8(b) that at $m = 0.8$, the NLC could not keep the 11-level output voltage, and also the peak voltage has significantly dropped to 342.6 V whereas for MQPSO based SHE-PWM, the voltage level was kept at 11-level and also the peak voltage was maintained comparatively better than NLC technique. Figure 8(a) and Figure 8(b) show that in SHE-PWM for the chosen modulation index, the required 5th, 7th, 11th, and 13th harmonics have been removed entirely. Further, since THD reduced by 3.62%, the overall harmonic profile improved. These findings check that the SHE-PWM control technique is superior to traditional NLCs with respect to THD. It is worth noting that SHE-PWM is usually applied to eliminating harmonics of lower order because it is the main reason why less torque is generated in the induction motors and overheat the transformer, conductors, and power lines [33]. In addition, high-order harmonics are frequently ignored, because with the help of the load impedance it can be

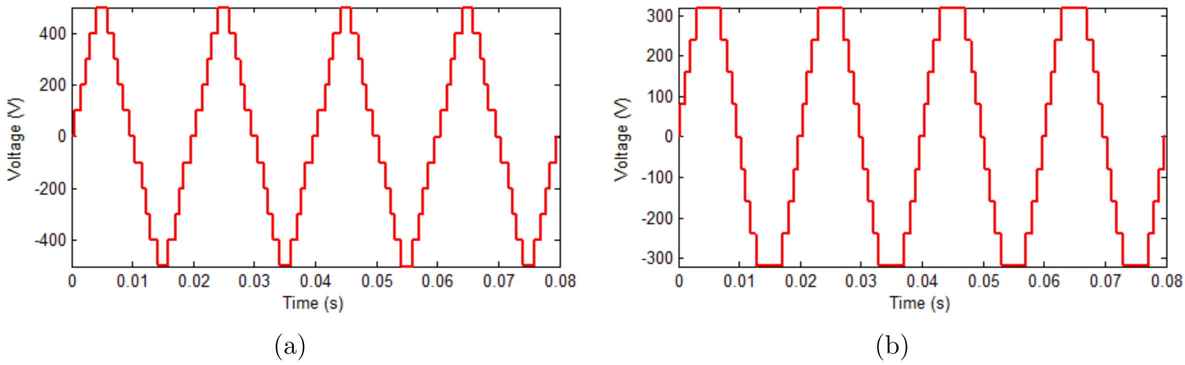

FIGURE 7. Simulation results of output voltage of CHB MLI: (a) MQPSO based SHE-PWM; (b) NLC

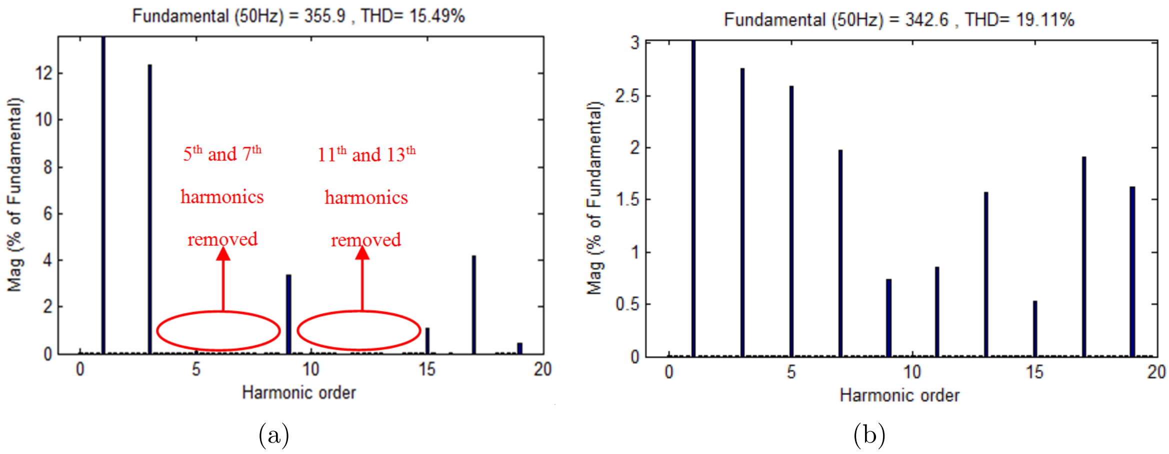

FIGURE 8. Simulation results of the harmonic spectrum: (a) MQPSO based SHE-PWM; (b) NLC

easily removed. The load impedance is proportional directly to the fundamental frequency. Therefore, the higher the harmonic order, the impedance added to those harmonics is increased and consequently magnitude becomes lower.

Advantage and disadvantage of the proposed techniques. From the above simulation, the main characteristics of the proposed technique for its success can be highlighted.

- The proposed technique can perform better than existing algorithms to tackle a highly nonlinear, multi-modal optimization problem.
- The proposed technique can overcome the disadvantage of premature convergence because it does not update its location based on the personal best information, and there is no explicit global best either.

5. **Conclusions.** For MLIs the modulation techniques are used to generate high-quality, efficient output power. Therefore, NLC and other popular PWM methods for multilevel inverter control are not considered efficient due to the high level of harmonics. To solve this problem, the SHE-PWM method based on MQPSO was implemented in this paper to reduce the number of harmonics defined to meet requirements in the application. In order to solve the transcendent equations, the mechanism is modified to eradicate the low order odd harmonics. The main conclusions of this study are

- Quantum techniques increase the diversity rate and find better results.
- THD reduced by 3.62%, the overall harmonic profile improved.
- Local attractor points in QPSO provide diversity.
- The quantum technique is less susceptible to premature convergence and is less likely to get stuck in local optima.

The key achievement of the paper is the successful execution of control systems along with the removal of harmonics of 5th, 7th, 11th, and 13th order. It involves empirical research into two distinct control procedures and simulated outcomes that show SHE-PWM's supremacy. The paper further showed the use of the novel MQPSO method which, together with valid simulation, recommends that this procedure can be used for any MLI-topology.

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