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SELECTIVE HARMONIC ELIMINATION PULSE WIDTH MODULATION (SHEPWM) FOR FIVE-PHASE NINE-LEVEL INVERTER USING IMPROVED WHALE OPTIMIZATION ALGORITHM

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Abstract

The multilevel inverter (MLI) is a well-known DC-AC converter system that can be used to convert renewable energy sources into industrial power sources. Compared to single-phase or three-phase MLI, five-phase MLI provide better output in terms of quality, efficiency and power. The harmonics in the MLI output voltage degrade the system's performance and reliability. Selected harmonic elimination pulse width modulation (SHEPWM) switching techniques are used to remove the lower order harmonics and lower the total harmonic distortion (THD). In recent years, a rapid evolution of optimization algorithms such as particle swarm optimization (PSO) algorithm, the genetic algorithm (GA) and whale optimization algorithm (WOA) are used to solve a complex equation such as SHEPWM non-linear equations. However, these algorithms were easy to fall into premature convergence and could not give the best result during the exploration and exploitation stage. In this paper, the improved whale optimization algorithm (IWOA), which is an improved version of the WOA is used as it has a better balance of exploration and exploitation which avoid premature convergence and is able to provide better results. The IWOA used to solve the non-linear equations for a five-phase nine-level inverter, and the results were compared to WOA, GA, and PSO for the whole modulation indexes (M). In comparison to all optimizations, the results indicate that the IWOA has a higher probability of reaching the global optimal. The proposed method efficiently computes the required switching angles for various M and eliminated the desired low order harmonics. The results show that the fifth, seventh, and eleventh harmonics have been removed from the output voltage of the five-phase, nine-level Cascaded H-Bridge Multilevel Inverter (CHBMLI).

Keywords: Five-phase, Improved whale optimization algorithm, Multilevel inverter, Optimization algorithm, Selective harmonic elimination PWM.

1. Introduction

The multilevel inverter (MLI) is regarded as a useful device to have in the power system, particularly because of its ability to harness renewable energy sources as power sources [1, 2]. It is well-known for its high efficiency and energy-saving capabilities. The MLI is also known for its low total harmonic distortion (THD), low switching stress, and increased efficiency [3]. The MLI has a flaw in that it frequently generates harmonic distortions, which cause problems in the power system. Low-order harmonics are more harmful to systems because they are similar to the fundamental frequency and have a large amplitude [4]. Due to inverter harmonics, switching losses in power switches increase, reducing system efficiency and performance. Interestingly, studies on switching schemes have been carried out and suggested as a solution to the problem. The proposed switching methods were sinusoidal pulse width modulation (SPWM), space vector modulation (SVM) and selective harmonic elimination pulse width modulation (SHEPWM) [5].

SHEPWM is the system for removing harmonics among researchers that is the most commonly used [6]. The challenge to use this approach however is finding suitable switching angles because of the difficulty of the method in solving issues for nonlinear equations [7]. Nevertheless, there are a number of approaches to nonlinear equation resolution, such as particle swarm optimization (PSO), genetic algorithm (GA), artificial bee colony (ABC), whale optimization algorithm (WOA) and others[7, 8]. For many decades, scholars and companies have paid close attention to multiphase systems [9, 10]. A multiphase system is one that uses more than one phase of power, such as three-phase, five-phase, or six-phase power. As the number of phases increases, multiphase systems have been shown to have more power, efficiency, and low distortion. As a result, the higher the phases, the better the system [11-13]. Therefore, five-phase MLI provide better output in terms of quality, efficiency and power compared to single-phase and three-phase MLI. MLI's advantages, such as improved output power waveform quality, lower harmonic distortions, and higher operating voltage capability, have aided in directing high voltage electrical power applications without the use of bulky transformers[14].

Based on the previous work[15], PSO is clearly capable of eliminating lower order harmonics and lowering THD in a nine-level inverter system by solving the SHEPWM non-linear equations. PSO results were compared to Newton-Raphson (NR) results for a nine-level inverter, and PSO performed significantly better in this study. Unfortunately, the study only looked into single-phase multilevel inverters. GA was also shown to be capable of solving non-linear SHEPWM equations. Based on the work[16], GA was programmed to solve SHEPWM non-linear equations for seven-level, eleven-level, and thirteen-level inverter systems and compared to isochronous switching (IS). The research results demonstrated that the GA-based SHEPWM switching technique outperforms the GA-based IS technique. However, this study was also conducted on a single-phase multilevel inverter. WOA, a recently discovered algorithm, can also be used for multilevel inverter systems. In a previous study[17], WOA was used for the SHEPWM switching technique on a fifteen-level inverter. The findings of this study demonstrate that WOA can solve non-linear equations and outperforms PSO. There are no multiphase inverter results in this study because it was done for single-phase multilevel inverters.

PSO, GA and WOA was not able to provide the best solutions as the algorithms is premature converge towards the solutions[18]. There is many research focus on single-phase and three-phase MLI, but not much research focus on five-phase MLI even though five-phase MLI are capable producing better outputs in term of quality, efficiency and power. Therefore, the Improve Whale Optimization Algorithm (IWOA) is used in this paper to minimise lower-order harmonics and satisfy the desired fundamental component in a five-phase multilevel inverter system. In addition, IWOA has been improve in terms of balancing the exploration and exploitation phase of algorithms which, avoid premature convergence and provide better solutions for MLI. WOA, GA, and PSO are used to compare with the IWOA algorithm. As a case study, a nine-level inverter was chosen.

2. Methodology

This section focuses on developing five-phase nine-level inverter using CHB topology. The algorithm, IWOA is design to solve the SHEPWM non-linear equations and finding the suitable switching angles for eliminating the selected lower order harmonics and reducing the THD from the MLI output. The simulations of five-phase nine-level inverter will be done according to the switching angles obtained from the algorithm. The performance of IWOA will be compared to PSO, GA and WOA based on the results obtain from the MLI simulations.

2.1. SHEPWM five-phase nine-level CHBMLI

Figure 1 depicts a five-phase, nine-level Cascaded H-Bridge Multilevel Inverter (CHBMLI) circuit diagram. CHBMLI is a single-phase full-bridge circuit composed of a series of H-bridge units, each of which generates voltage outputs of + V_{dc}, 0 and $-V_{dc}$ [19].

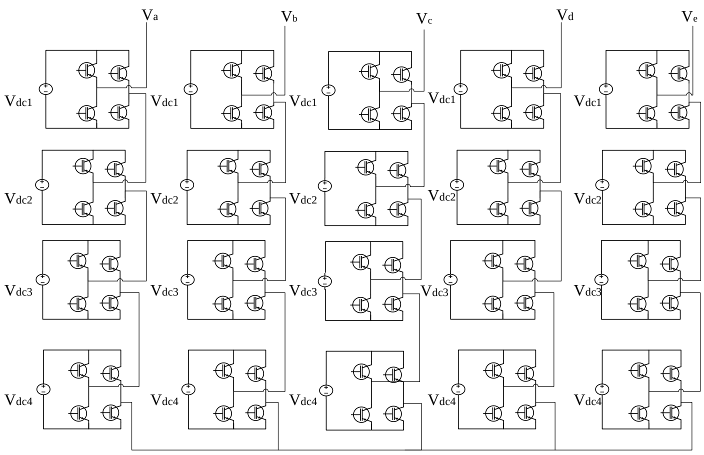


Fig. 1. Circuit of five-phase nine-level CHBMLI.

A five-phase MLI is created by cascading a single-phase full-bridge circuit five times in parallel. Equation **Error! Reference source not found.** denotes the system's level formula, where *m* denotes the output level of the system and *s* denotes the number of H-bridge units per phase[20].

$$m = 2s + 1 \tag{1}$$

One of the main benefits of SHEPWM, according to the author, is the elimination of lower order harmonics [21]. Unfortunately, incorporating SHEPWM methods into the scheme required the use of pre-calculated switching angles, which is a time-consuming process that becomes more difficult as more harmonics are removed [22, 23]. The general view waveform of a nine-level MLI is shown in Fig. 2. According to Fig. 2, in order to create a nine-level inverter, four switching angles must be calculated: α_1, α_2, α_3 and α_4.

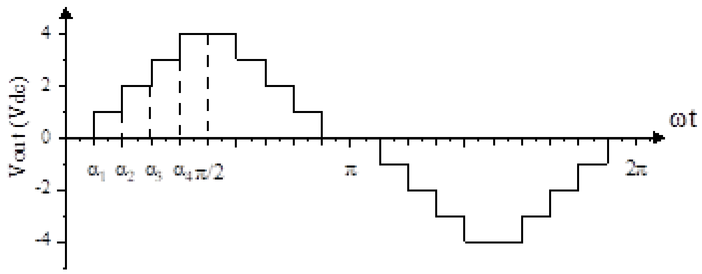


Fig. 2. General view of nine-level MLI output waveform.

Equation (2) shows the Fourier series expansion of a nine-level inverter[20].

$$V_{AN}(wt) = \sum_{n=1,3,5\ldots}^{\infty} \frac{4V_{dc}}{np} [V_{dc1}Cos(n\alpha_1) + (V_{dc2}Cos(n\alpha_2)) + (V_{dc3}Cos(n\alpha_3)) + (V_{dc3}Cos(n\alpha_3)) + (V_{dc4}Cos(n\alpha_4))]Sin(nwt) \quad (2)$$

where V_{dc} is the input voltage of each H-bridge, and the DC source is equal for all, $V_{dc1} = V_{dc2} = V_{dc3} = V_{dc4} = 48$ V.

$$0 < \alpha_1 < \alpha_2 < \alpha_3 < \alpha_4 < \frac{\pi}{2} \quad (3)$$

In order to obtain the correct waveforms, the input switching angle must follow the condition in Equation (3). Since the system is a five-phase system, the quintuple harmonics (5th, 15th, 25th, 35th, and more) would be self-eliminated in balanced five-phase system. Therefore, the chosen lower order harmonics that must be eliminated are the 3rd, 7th, and 9th harmonics. Equations (4) can thus be used to determine the system's proper switching angles[20].

$$\begin{aligned} &Cos(\alpha_1) + Cos(\alpha_2) + Cos(\alpha_3) + Cos(\alpha_4) = M \\ &Cos(3\alpha_1) + Cos(3\alpha_2) + Cos(3\alpha_3) + Cos(3\alpha_4) = 0 \\ &Cos(7\alpha_1) + Cos(7\alpha_2) + Cos(7\alpha_3) + Cos(7\alpha_4) = 0 \\ &Cos(9\alpha_1) + Cos(9\alpha_2) + Cos(9\alpha_3) + Cos(9\alpha_4) = 0 \end{aligned} \quad (4)$$

where M is the modulation index which defines as:

$$M = \pi V_1 / (4V_{dc}) \quad (5)$$

where V_1 is the fundamental voltage, and V_{dc} is the input voltage.

SHEPWM technique was unable to obtain a solution that eliminated the selected harmonics for some modulations, according to [24]. Thereby, the algorithm must be able to obtain the fundamental at a certain level while minimizing and preferably eliminating the undesirable lower order harmonics. Consequently, Equation (6) is the objective function, f proposed for use in this analysis[25]. The switching angles are calculated from 0° to 90° using a modulation index of 0.1 to 1 for a step size of 0.01.

This equation keeps the fundamental, V_1, as close to the desired value, V_{ref} as possible while limiting the selected lower order harmonics, 3rd, 7th, and 9th harmonics to less than 1% of the fundamental value and increasing the chances of elimination by dividing the harmonic ratio with its own harmonic.

$$f(\alpha)=\left[(100*\frac{V_{ref}-V_1}{V_{ref}})^4+\left(\frac{1}{3}(50*\frac{V_3}{V_1})^2\right)+\left(\frac{1}{7}(50*\frac{V_7}{V_1})^2\right)+\left(\frac{1}{9}(50*\frac{V_9}{V_1})^2\right)\right] \quad (6)$$

Based on the preceding equations, it is difficult to manually solve every equation in a short period of time. Optimization problems, particularly in non-linear equations, frequently result in linearisation and non-convergence. Fortunately, researchers have proposed a number of solutions for overcoming the equation's intricacy. Natural-inspired evolutionary approaches have evolved and are being applied to a wide range of optimization tasks. Metaheuristic algorithms such as Newton-Raphson (NR), PSO, and GA have been shown to be effective in addressing these types of problems [25-31]. Other than PSO and GA, recently discovered algorithms such as Artificial Bee Colony (ABC), Grey Wolf Optimization (GWO), and WOA have been shown to effectively solve non-linear equations [32-35]. IWOA was used to solve a non-linear equation related to SHEPWM for a five-phase nine-level inverter in this analysis.

2.2. Whale optimization algorithm

The Whale Optimization Algorithm (WOA), developed by Seyedali Mirjalili in 2016, is a relatively new algorithm[36]. WOA is based on a hunting technique used by humpback whales known as bubble-net feeding. WOA employs three mathematical models: the first is encircling prey, the second is bubble-net feeding (exploitation), and the third is finding prey (exploration). This document provides a comprehensive overview of the mathematical model for WOA [35, 36]. The first method, encircling prey, involves the initialization of each search agent (solutions). This method can be expressed mathematically as shown in Equations (7) and Equations (8)[36]. t is the number of iterations, X^* is the current position found thus far, and A and C are coefficients calculated in Equations (9) and (10) respectively[36]. r_1 and r_2 are random numbers ranging from 0 to 1, and a is a variable that decreases linearly from 2 to 0 with each iteration.

$$D=|C.X^*(\mathrm{t})-X(\mathrm{t})| \quad (7)$$

$$X(t+1)=X^*(t)-A.D \quad (8)$$

$$A=2a.r_1-a \quad (9)$$

$$C=2r_2 \quad (10)$$

The second method, bubble-net feeding, evaluates the solutions in order to determine the best solution (Leader score) and its position (Leader position). This method updates the search agent position in two steps: shrinking encircling and spiral updating position. Each step is assigned the same probability. The mathematical expression for the bubble-net feeding method is shown in Equation (11) where b is a constant that determines the logarithmic spiral shape, l and r are random numbers (0,1)[36].

$$X(j+1)=\begin{cases} X^*(t)-A.D & \text{if } r \le 0.5 \\ D'.e^{bl}.COS(2\pi l)+X^*(t) & \text{if } r \ge 0.5 \end{cases} \tag{11}$$

The final method, finding prey is method to update and control the movement of each search agent in search of better solution. Instead of controlling the best agent, this method controls random whale to move finding better solutions as [37, 38]shown in Equation (12). Its position will be update according to Equation (13) if the solutions when $A \ge 1$[36].

$$D = | C.X_{rand}(\mathrm{t}) - X(\mathrm{t}) | \tag{12}$$

$$X(t+1) = X_{rand}(t) - A.D \tag{13}$$

The further explanations on application of WOA can be referred in this work. Figure 3 shows the flowchart of WOA approach. The objective function outcomes of the WOA will be based on Leader score and Leader position, and these factors will serve as the key determining factors for the suitable switching angles for the MLI.

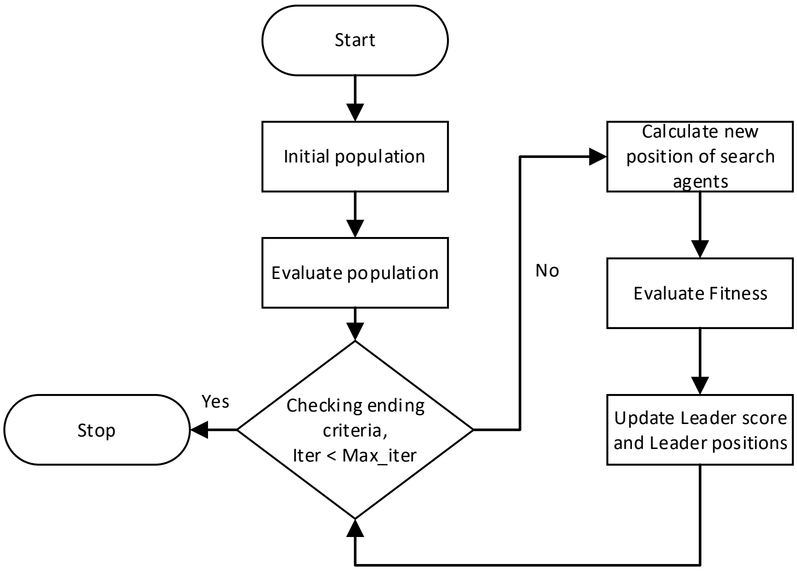


Fig. 3. The flowchart of WOA approach.

2.3. Improved whale optimization algorithm

As the name implies, Improved WOA (IWOA) is an improved version of WOA. Some studies have been conducted to improve WOA performance in order to solve specific problems and further improve WOA performance. IWOA was introduced in previous work [39], for parameter identification of a hydraulic turbine at no-load. IWOA is capable of identifying hydraulic turbine parameters and solving estimated parameter range uncertainty problems by increasing the global exploration probability and introducing immune operators into WOA, including adaptive modification methods. The experimental results show that IWOA has higher precision, faster convergence, and higher reliability than WOA. Previous work, [40], also mentioned several additional types of IWOA that have been developed. For his studies, this researcher also created IWOA. IWOA is introduced in his research by combining the WOA exploration phase (finding prey) with Differential Evolution (DE) mutations in order to improve WOA exploration and exploitation. The results of the experiments show that IWOA outperforms WOA.

The IWOA used in this work was adapted from the work of [41]. The researcher creates IWOA to counter balance WOA probability when selecting exploration and exploitation phases. WOA clearly favors early convergence to local optima over exploring more effective solution. As a result, the researcher proposed that WOA be improved by changing Equations (8) to Equation (14) and Equation (13) to Equation (15)[41].

$$X(t+1) = X_{rand1} - A.|X^*(t) - X_{rand1}(t)| \tag{14}$$

$$X(t+1) = X_{rand2}(t) - A.|X(t) - X_{rand2}(t)| \tag{15}$$

The proposed IWOA improves the WOA in three ways: increasing population diversity, achieving a balance between exploration and exploitation, and increasing robustness. As shown in Fig. 3, IWOA continues to function similarly to WOA. Figure 4 shows the algorithm's improvements.

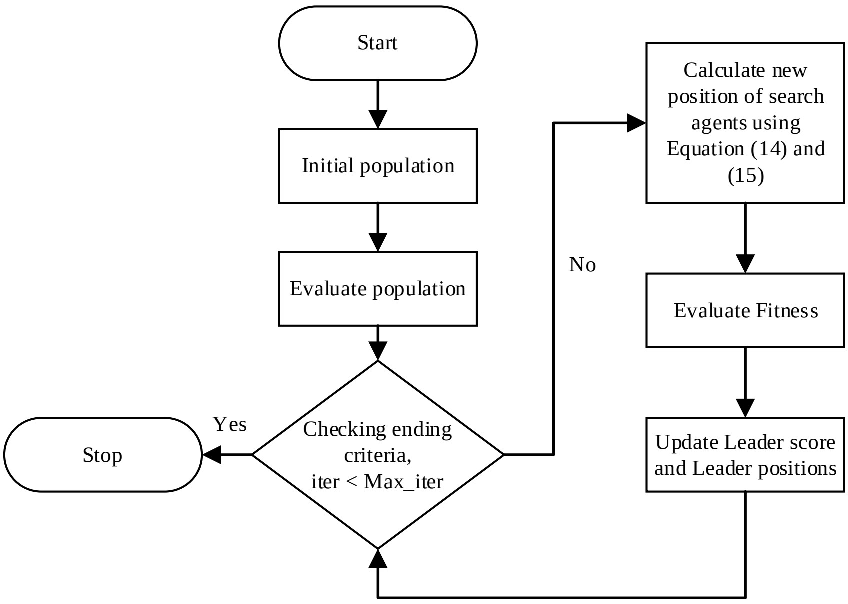


Fig. 4. The flowchart of IWOA approach.

IWOA was used in this study to solve the SHEPWM non-linear equation for a five-phase nine-level MLI system. When Equation (4) is applied to IWOA, the algorithm would then find suitable firing angles while excluding selected lower order harmonics, 3^{rd}, 7^{th}, and 9^{th} for the entire modulation index. The solutions are then evaluated using the objective function, as outlined in Equation (6). The lowest possible value of the evaluation obtained shows an excellent solution (firing angles) suitable for five-phase nine-level MLI. The analysis was based on the IWOA results.

3. Results and Discussion

IWOA is used in this analysis to solve the SHEPWM for various modulation index values. In terms of efficiency and accuracy of the solutions obtained, PSO, GA, and WOA were chosen to compare with IWOA. As shown in Table 1, all four algorithms were configured with the same parameters. The results have a range of $0.01 \leq M \leq 1.00$, which shows the firing angles obtained from the algorithms after solving the SHEPWM non-linear equations. In this case, it can be demonstrated that the results for each algorithm used are complementary to the constraint in Equation (3), namely that α_1 is less than α_2, α_2 is less than α_3 and α_3, is less than α_4. Furthermore, as shown in Fig. 5, the angles obtained from all four algorithms are nearly identical. This reveals that the computing capability of these algorithms is essentially equal.

Table 1. Parameters used for PSO, GA, WOA and IWOA.

	PSO	GA	WOA	IWOA
No. of Particle/Search agents	100	100	100	100
No. of Iteration	200	200	200	200

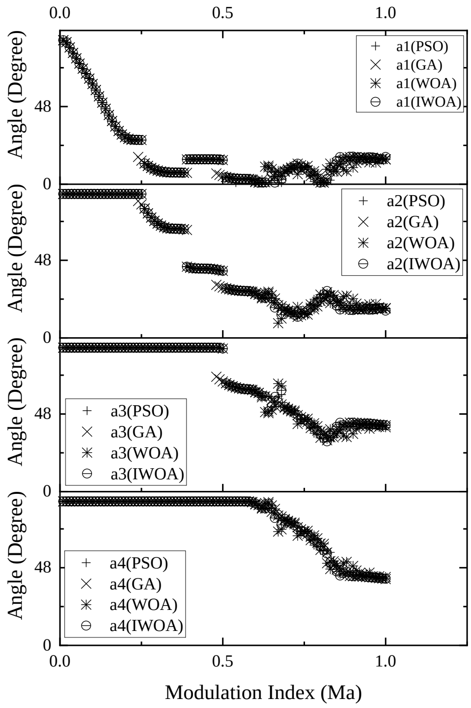


Fig. 5. Graph of switching angles obtained from PSO, GA, WOA and IWOA.

Figure 6 presents the graph of the objective function obtained from the algorithms for solving the SHEPWM switching technique. According to the results, IWOA performed slightly better in accuracy, followed by GA, WOA, and PSO to solve the equation. IWOA demonstrated significantly greater potential in solving non-linear equations and obtaining the lowest possible results when compared to PSO, GA, and WOA, as IWOA obtained the lowest global minima (3.95×10^{-13}), followed by GA (8.083×10^{-13}), WOA (1.634×10^{-09}), and PSO (6.27×10^{-07}). The Cumulative Distribution Function (CDF) is a curve that depicts the algorithm's speed of convergence in locating global minima (solution). To demonstrate the convergence speed of the algorithms, the CDF is applied to the objective function results of PSO, GA, WOA, and IWOA. Figure 7 clearly shows that IWOA has a better CDF curve than PSO, GA, and WOA. At CDF (10^{-5}), IWOA is capable of obtaining a solution at 29% of the modulation index range, WOA at 20% of the modulation range, and GA and PSO at 17% of the modulation index range. Therefore, IWOA clearly outperforms in solving the SHEPWM non-linear equation. Table 2 displays the summary results for PSO, GA, WOA, and IWOA. Figure 8 represents the percentage of 3rd, 7th, and 9th harmonics for each algorithm, PSO, GA, WOA, and IWOA. The results show that selected harmonics (3rd, 7th, and 9th) can be eliminated at modulation indexes ranging from 0.4 to 1.0 for PSO, GA, WOA, and IWOA. According to the MATLAB results, IWOA outperforms PSO, GA, and WOA in terms of efficiency and accuracy. It is also mathematically capable of eliminating selected 3rd, 7th, and 9th harmonics.

Table 2. Summary results of Objective function and CDF curve for PSO, GA, WOA and IWOA.

	Lowest objective function obtained	Percentage of convergence speed at CDF(1×10^{-5})
PSO	6.278×10^{-07}	17%
GA	8.083×10^{-13}	17%
WOA	1.634×10^{-09}	20%
IWOA	3.951×10^{-13}	29%

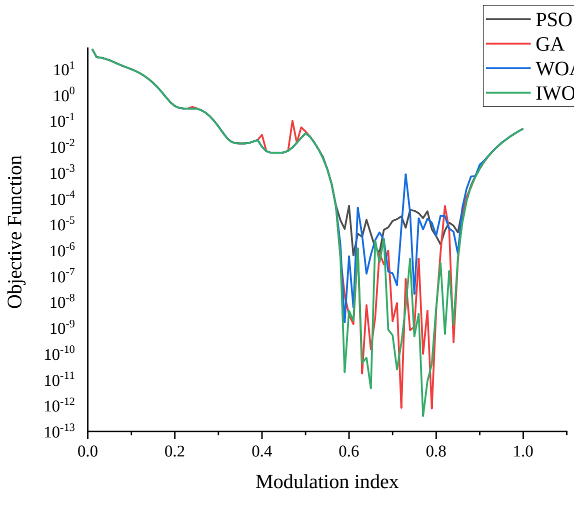


Fig. 6. Graph of objective function against modulation index obtain from PSO, GA, WOA and IWOA.

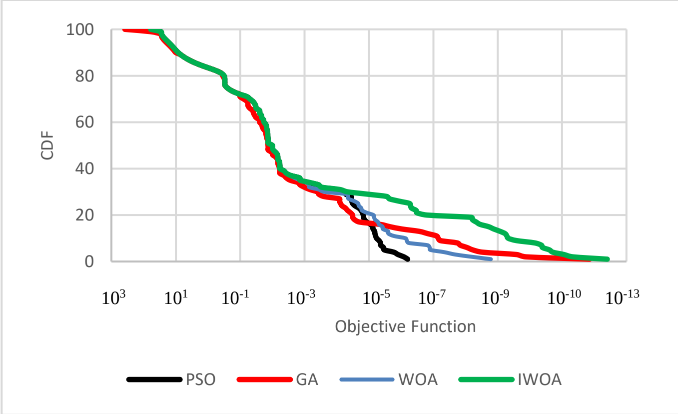


Fig. 7. CDF curve for PSO, GA, WOA and IWOA.

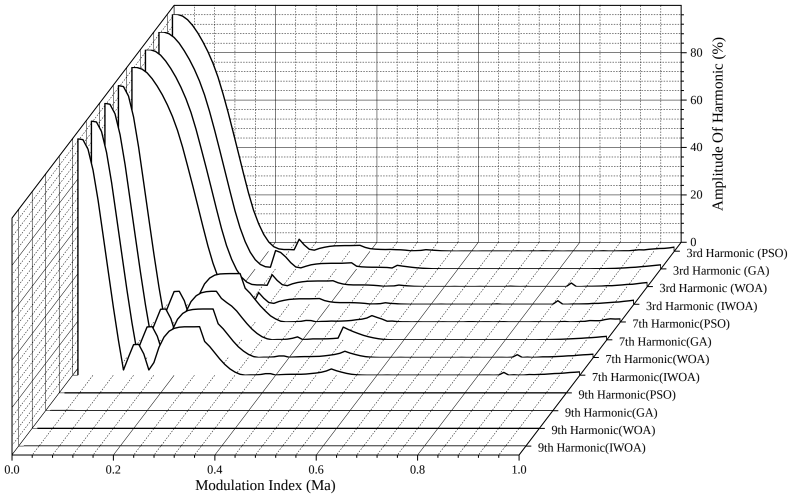


Fig. 8. Graph of harmonic amplitude for 3rd, 7th and 9th harmonics for PSO, GA, WOA and IWOA.

For the simulation, the CHBMLI system's input voltage (48V) was distributed evenly. The switching angle inputs for this study were chosen from the best PSO, GA, WOA, and IWOA results. Table 3 until Table 6 show the simulation results for PSO, GA, WOA, and IWOA, respectively. According to the results, all algorithms were able to reduce THD below 20%, with IWOA achieving the lowest THD value of 8.48% at modulation 0.84. Figures 9 to 11 show graphs of the phase voltage waveform, line-to-line voltage waveform, and harmonic spectrum of line-to-line voltage (V_{AB}) obtained from PSIM simulation for IWOA at modulation index of 0.57, 0.68, and 0.84, respectively. According to the results, all phase voltage waveforms are capable of producing a good sinusoidal staircase waveform, similar to the general waveform shown in Fig. 2.

The harmonic spectrum of line-to-line voltage (V_{AB}) of the nine-level five-phase CHBMLI for IWOA clearly shows that the selected low order harmonics, 3rd, 7th, and 9th, as well as the quintuple harmonics, 5th, 15th, 25th, and others, are eliminated.

The first harmonic that appears in all three results is the 11th harmonic. Therefore, IWOA can eliminate selected lower order harmonics.

Table 3. PSO simulation results.

Modulation Index	Angles applied α_1	α_2	α_3	α_4	THD (simulation)	Objective Function, *f*
0.57	3.17˚	29.04˚	63.44˚	89.00˚	17.70 %	5.32×10^{-05}
0.68	1˚	17.06˚	59.97˚	77.09˚	14.65%	6.19×10^{-06}
0.84	11.22˚	23.03˚	36.95˚	48.87˚	12.26 %	4.87×10^{-6}

Table 4. GA simulation results.

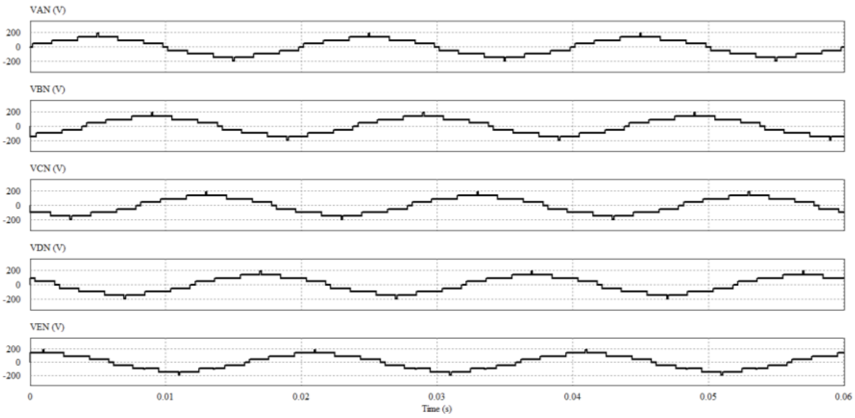
Modulation Index	Angles applied α_1	α_2	α_3	α_4	THD (simulation)	Objective Function, *f*
0.57	3.28˚	29.02˚	63.34˚	88.99˚	17.64 %	4.63×10^{-05}
0.68	4.12˚	13.02˚	64.12˚	73.02˚	12.68%	2.82×10^{-07}
0.84	12.13˚	22.15˚	37.85˚	47.87˚	10.24 %	2.83×10^{-10}

Table 5. WOA simulation results.

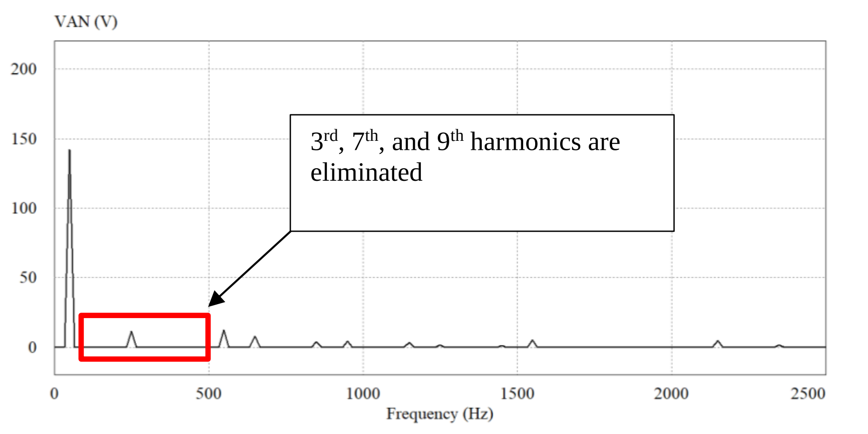
Modulation Index	Angles applied α_1	α_2	α_3	α_4	THD (simulation)	Objective Function, *f*
0.57	3.29˚	29.02˚	63.34˚	89.00˚	17.64 %	4.63×10^{-05}
0.68	4.92˚	12.02˚	65.42˚	71.72˚	13.98%	2.54×10^{-06}
0.84	8.03˚	26.49˚	33.54˚	51.94˚	12.19 %	5.22×10^{-06}

Table 6. IWOA simulation results.

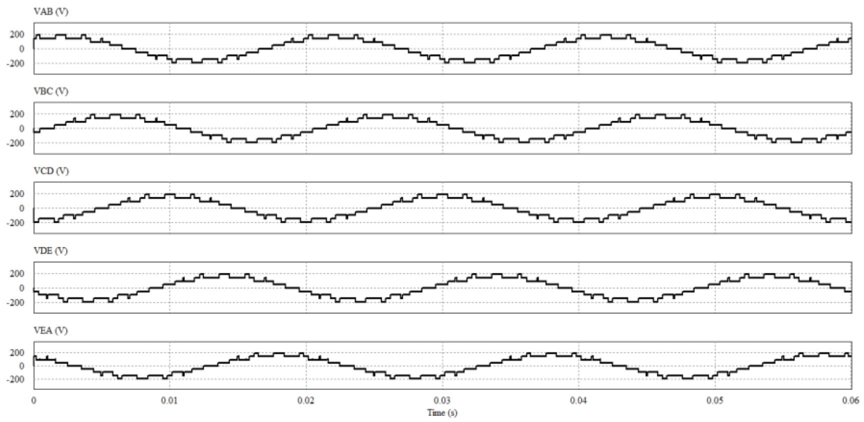
Modulation Index	Angles applied α_1	α_2	α_3	α_4	THD (simulation)	Objective Function, *f*
0.57	3.28˚	29.02˚	63.34˚	89˚	17.62 %	4.63×10^{-05}
0.68	3.06˚	14.35˚	62.65˚	74.49˚	11.36 %	2.80×10^{-06}
0.84	10.42˚	23.86˚	36.14˚	49.58˚	8.48 %	1.33×10^{-09}



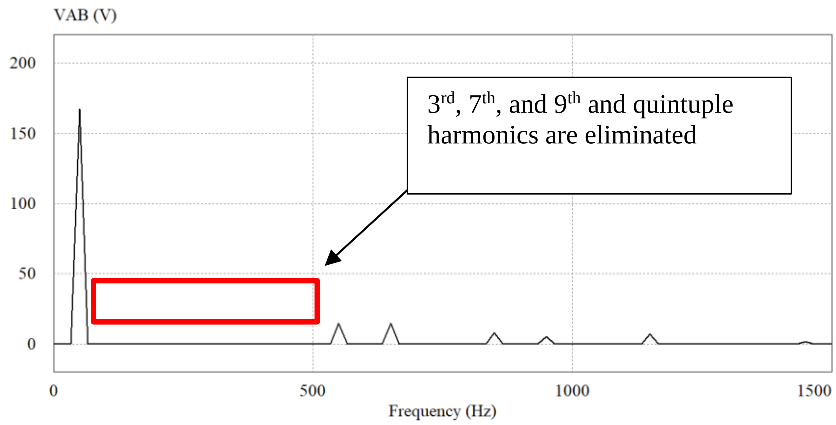
(a) Phase voltage output waveform.



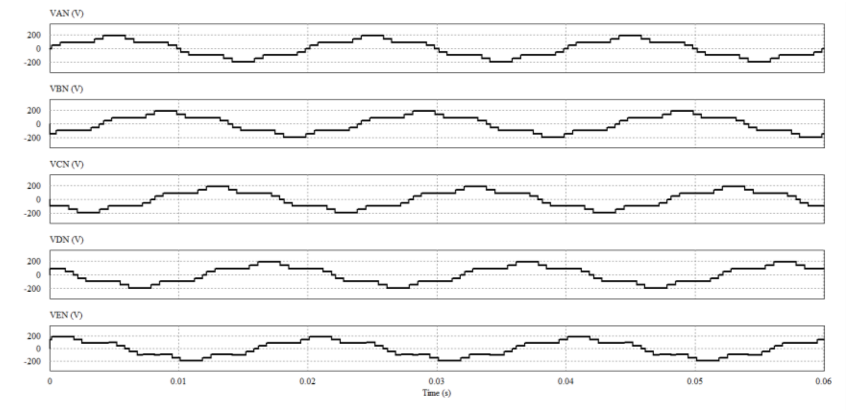
(b) Harmonic spectrum of phase voltage (V_{AN}).



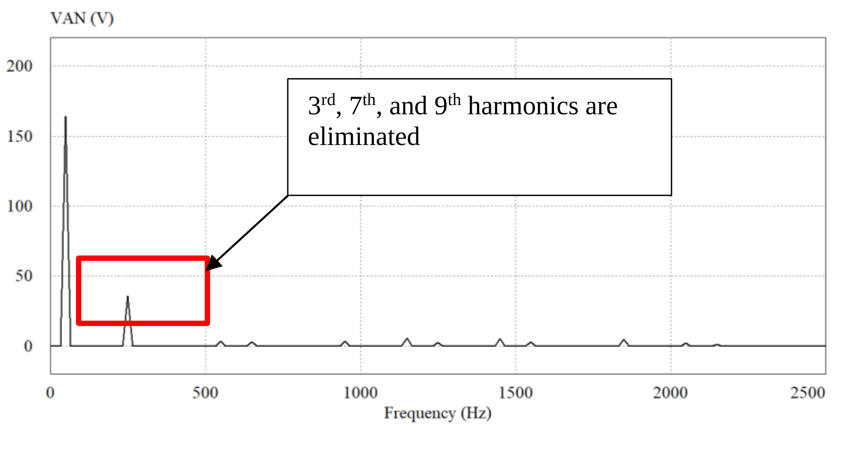
(c) Line-to-line voltage output waveform.



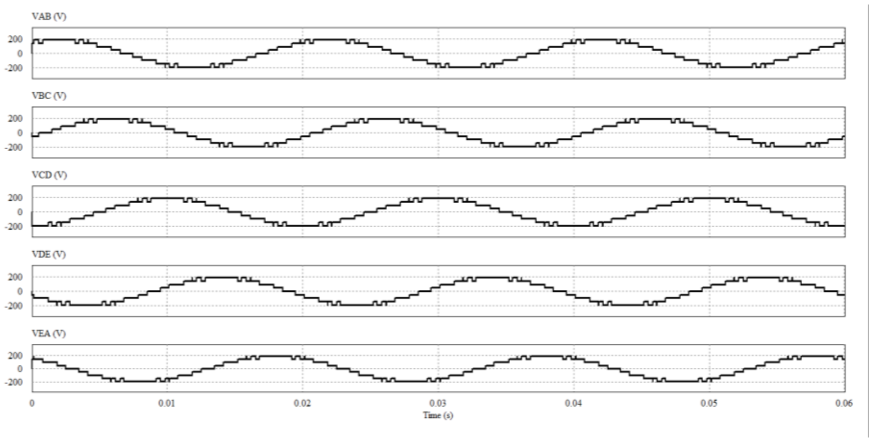
(d) Harmonic spectrum of line-to-line voltage (V_{AB})
Fig. 9. Results of five-phase nine-level inverter output at M = 0.57.



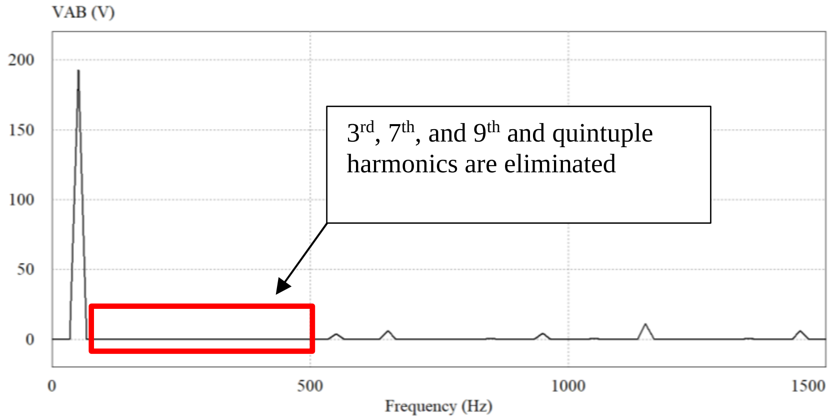
(a) Phase voltage output waveform.



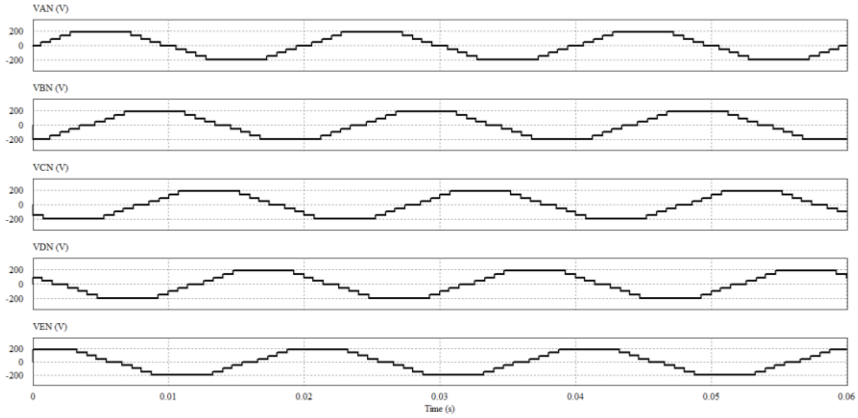
(b) Harmonic spectrum of phase voltage (V_{AN}).



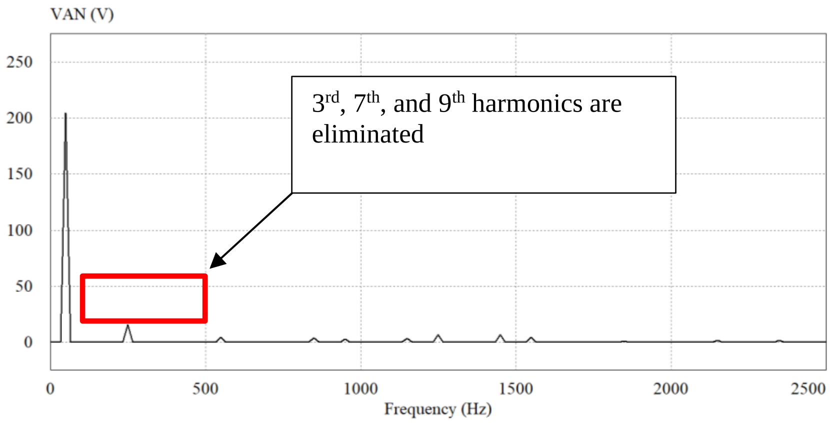
(c) Line-to-line voltage output waveform.



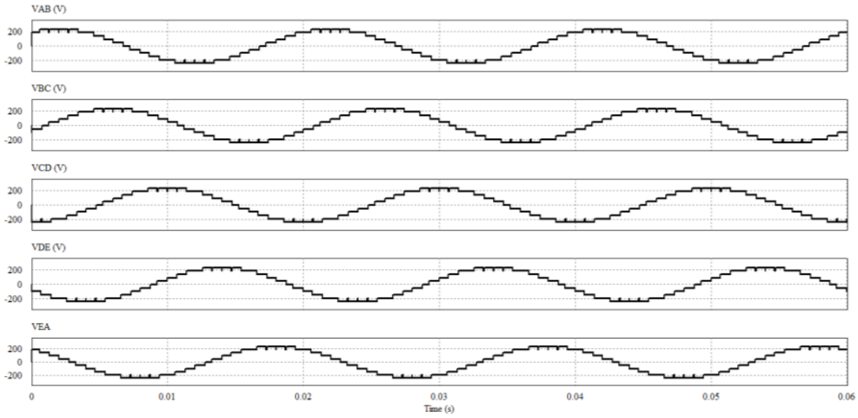
(d) Harmonic spectrum of line-to-line voltage (V_{AB})
Fig. 10. Results of five-phase nine-level inverter output at M = 0.68.



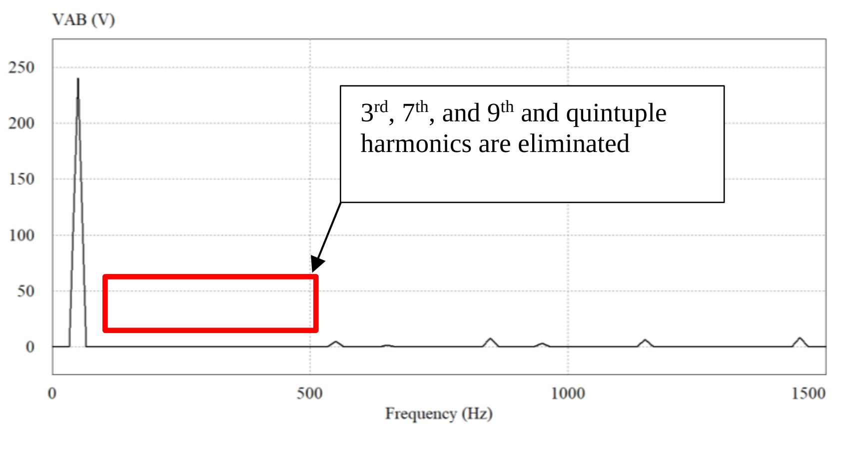
(a) Phase voltage output waveform.



(b) Harmonic spectrum of phase voltage (V_{AN})



(c) Line-to-line voltage output waveform.



(d) Harmonic spectrum of line-to-line voltage (V_{AB}).

Fig. 11. Results of five-phase nine-level inverter output at M = 0.84.

4. Conclusion

In this paper, IWOA is an enhanced version of WOA that increases population diversity, achieves equilibrium between exploration and exploitation, and increases the algorithm's robustness. The algorithm, IWOA was then used to fix the SHEPWM non-linear equation for a five-phase nine-level inverter. To demonstrate the efficiency of IWOA in solving the SHEPWM non-linear equation, well-known optimization algorithms such as PSO, GA, and WOA were used to compare with IWOA solving the equation. According to the MATLAB results, all algorithms are capable of solving the non-linear equation and removing the chosen lower order harmonics.

For the conclusions, the application of IWOA into a five-phase, nine-level CHBMLI was thoroughly examined in simulations. IWOA has clearly demonstrated that IWOA is capable of solving the SHEPWM non-linear equation. IWOA can also be used effectively with the MLI system and other optimization algorithms. In terms of IWOA, this newly discovered algorithm demonstrated in simulations that it can be as efficient as traditional algorithms like PSO and GA while outperforming WOA. IWOA is also capable of removing the selected harmonics, 3^{rd}, 7^{th}, and 9^{th}, as well as reduced lower order harmonics and reduced THD as low as 8.48% for five-phase nine-level inverter.

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