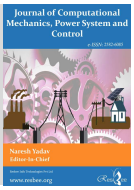
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Selective Harmonic Elimination in a Multilevel Inverter Using a Hybrid Optimization Algorithm

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Abstract: Multilevel Inverters (MLI) employ a technique called Selective Harmonic Elimination (SHE) to lessen undesired harmonics in the output voltage waveform. This technique is widely adopted in power electronics because lower-order harmonics significantly deteriorate power quality and reduce the efficiency of power conversion systems. This is accomplished by carefully choosing switching angles that preserve the intended fundamental frequency component while removing particular lower-order harmonics. In order to solve the SHE problem for a multilevel inverter design with a Cascaded H-Bridge Multilevel Inverter (CHB-MLI), this research suggests a hybrid approach with the combination of Cuckoo Search Algorithm (CSA) and Whale Optimization technique (WOA), also called as CS-WOA, which significantly reduces computing time and enhances the accuracy of the SHE solution. The novelty of the proposed hybrid method lies in exploiting the global search capabilities of CSA and the fast convergence ability of WOA, thereby creating a balanced optimization framework. This model eliminates the selective harmonics in the Multilevel Inverter (MLI). In the exploration phase, the hybrid method quickly searches the whole SHE problem's search space and returns initial switching angle values for a given modulation index. This ensures that the algorithm avoids local optima traps and provides robust initial solutions for further refinement. The comparison of the convergence performance for different methods and overall harmonic distortion against various modulation index values is performed. The experimental results show that the suggested model produced greater harmonic elimination accuracy when compared to the other existing models. Thus, the multi-level inverter's SHE is experimentally validated and examined.

Keywords: Cascaded H-Bridge Inverter, Multilevel Inverter; Cuckoo Search; Whale Optimization Algorithm; Selective Harmonic Elimination Pulse Width Modulation

Nomenclature

Abbreviation	Description
SHE-PWM	Selective Harmonic Elimination Pulse Width Modulation
PV	Photovoltaic
GA	Genetic Algorithm
SHE	Selective Harmonic Elimination
NR	Newton–Raphson
MLI	Multilevel Inverter
PSOGWO	Hybrid Particle Swarm Optimization with Gray Wolf Optimization
CSA	Cuckoo Search Algorithm
WOA	Whale Optimization Algorithm
FPA	Flower Pollination Algorithm
CHB-MLI	Cascaded H-Bridge Inverter Multilevel Inverter
CS- WOA	Cuckoo Search Whale Optimization Algorithm
DC	Direct Current
PSO	Particle Swarm Optimization
TLBO	Teaching-Learning Based Optimization
ABC	Artificial Bee Colony
ICA	Imperialistic Competitive Algorithm
HS	Harmony Search
CHB	Cascaded H-Bridge inverter
MPA	Marine Predator Algorithm
PLECS	Piecewise Linear Electrical Circuit Simulation
ACO	Ant Colony Optimization
MHB	Modified H-Bridge
THD	Total Harmonic Distortion
AC	Alternative Current
ELR	Egg Laying Radius
FFT	Fast Fourier transform

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1. Introduction

As an alternate power range, the MLI structure is used. It has become a promising solution for medium and high-power applications due to its modularity and scalability. The fundamental idea behind MLI is that it employs some low-rated semiconductor switches and numerous Direct Current (DC) inputs to create stepped waveform stress at greater power rates [1]. This stepped voltage output closely resembles a sinusoidal waveform, which helps in reducing the filtering requirements at the load side. Certain topologies of MLI allow the use of various power sources, including several inputs. Using the proper algorithms, power switches are managed. Similarly, MLI has several advantages, and significant drawbacks such as waveform distortion from low-order harmonics, which lowers their efficiency and performance in addition to reducing the system's lifespan [2]. Therefore, advanced modulation techniques are essential to maintain the balance between harmonic performance, efficiency, and switching stress. These include low switching frequency-based approaches like Selective Harmonic Elimination Pulse Width Modulation (SHEPWM) and space vector control. However, high switching frequency-based modulation techniques like sinusoidal pulse width modulation, space vector pulse width modulation, etc., are given in [3]. According to the literature, the SHEPWM approach is more important for multilevel inverter control. This is because it can operate switches at fundamental frequency while controlling undesirable low-order harmonics [4].

Certain applications require the ability to reach a greater range of Modulation Indices (Mis). Thus, some studies aim to expand the range of MI. Achieving a wide modulation index range is crucial for adapting the inverter performance under varying load and input conditions. In [5], real-time solutions are suggested. Although these techniques cover a large range of MI, they are unable to ensure that the output voltage's lower-order harmonic components are removed. Furthermore, they are not pertinent to high-level MLIs. In [6], the Groebner bases and symmetric polynomials-based MI range extension are taken into consideration for three-level inverters. Eight switching angles are used in this way to increase the MI range, but they are not a full range. Furthermore, in higher-level MLIs, this method is ineffective for extending the MI range. This limitation highlights the need for optimization strategies that can scale efficiently with increasing inverter levels. Optimal switching angles and fixed uneven DC sources have been suggested in various works. These techniques were unable to considerably increase the MLI range. In [7], fixed DC sources are suggested alongside an extension of switching angles in the region of zero. The SHE with half-wave symmetry is universally formulated in reference [8].

Generally, SHE equations are solved using meta-heuristic algorithms like the Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Whale Optimization Technique [9]. However, not every modulation index can be solved by any one algorithm. This motivates hybrid approaches, where the strengths of multiple optimization techniques are combined to achieve higher robustness. As a result, researchers concentrate on novel optimization techniques. Furthermore, the majority of approaches to solving the SHE equations make the assumption that all DC sources are equal. Nonetheless, in certain real-world scenarios, such as in renewable energy applications like fuel cell and solar panel systems [10], variations in DC sources would have a significant effect on the Total Harmonic Distortion (THD). Hence, a more flexible algorithm that can handle non-ideal input conditions becomes highly desirable. To solve a SHE problem in MLI, a new CS-WOA is proposed to handle the SHE problem when the input voltages in the MLI are fluctuating. Comparing it to its existing approaches, such as PIO, GA, PSO, and GSA, the proposed model is far faster and more reliable. The hybrid CS-WOA framework intelligently balances exploration and exploitation, ensuring faster convergence toward optimal switching angles. The outcomes of the simulation show that the accuracy of the CS-WOA method is in CHB-MLI.

The contribution of the paper is given below,

- To suggest a SHE in a CHB-MLI to eliminate specific harmonic components in the output voltage waveform through handling the essential voltage.
- To introduce a hybrid optimization algorithm by combining the combination of CSA and WOA methods to improve the effectiveness of SHE for enhancing SHE efficiency. It also gives better harmonic reduction and decreases the THD in the inverter output.

The organization of the paper is listed as follows: Section 2 represents the related work of the implemented SHE model in MLI. Section 3 gives the methodology that which used in the multilevel inverter for harmonic elimination. Section 4 shows the result and discussion of the SHE of the multilevel inverter with an optimized algorithm. Finally, the conclusion of the proposed model is settled in Section 5.

2. Literature Survey

2.1 Related Work

The related existing papers of the suggested optimized algorithm-based multilevel inverter to eliminate selective harmonics in the model are given below,

In 2023, Khizer et. al [11] proposed the multi-criteria search-based enhanced firefly algorithm for solving SHE in a multilevel inverter. To find the optimal global search, the improved firefly algorithm was used adaptive nature of cognitive and social mechanisms. Similarly, the 3-phase 9-level cascaded MLI could calculate the results and identify the suggested algorithm's efficiency. In the analysis of convergence, the fitness value was decreased with a smaller number of iterations. Thus, the result of the model showed that the firefly and particle swarm optimization obtained the highest efficiency. Lastly, the SHE of MLI was experimentally validated and achieved. This study highlighted the importance of balancing convergence speed with accuracy, showing that hybrid or improved versions of swarm-based algorithms can outperform conventional methods.

In 2021, Padmanaban et. al [12] implemented an optimization method for selective harmonic elimination in a cascaded MLI using Teaching-Learning Based Optimization (TLBO). The suggested approach could solve the nonlinear equations and identify the best solution in order to eliminate low-order harmonics while still satisfying the fundamental component. The model examined the impact of ideal DC sources to achieve the SHE in the inverter by comparing the existing optimization model. To improve the SHE's performance, the model presented the TLBO, which was a newly established algorithm. The results of the simulation demonstrate that TLBO was superior to the existing methods with higher precision and convergence probability. One of the strengths of TLBO is that it does not require algorithm-specific control parameters, which makes it more user-friendly compared to GA or PSO.

In 2023, Sajid et. al [13] demonstrated the SHE-PWM approach in MLIs, with a 9-level asymmetric Cascaded H-Bridge (CHB) inverter topology and a 5- and 7-level Modified H-Bridge (MHB) topology, using the Runge–Kutta (RUN) metaheuristic optimization algorithm. For MLIs, the MI was changed from increments of 0.01 to 1.0 to determine the switching angles. The suggested RUN approach performed better by the function values, procedure reliability, and THD values taken from the simulation data. The outcomes verified that the fifth and seventh harmonics were eliminated in 5-, 7-, and 9-level MLIs, effectively. This work proved that novel mathematical-inspired algorithms like RUN can compete with bio-inspired methods, especially when harmonic elimination precision is critical.

In 2024, Kala et. al [14] presented a hybrid method to solve the SHE problem for an adaptive DC bus MLI topology. The suggested hybrid approach significantly reduces calculation time and enhances the accuracy of the SHE solution by combining the Newton-Raphson (NR) numerical method with the GWO. Based on a few important performance metrics, the efficiency of the SHE method was compared with the performance of metaheuristic SHE approaches. Lastly, a small-scale prototype was created to confirm the suggested approach. An efficiency of the GWO-NR SHE approach had been demonstrated with the simulation and experimental findings, which showed a fast dynamic and excellent control over the targeted harmonics in the standalone PV system. This combination of a numerical method with a metaheuristic strategy highlights the emerging trend of hybrid optimization techniques in SHE research.

In 2021, Riad et. al [15] explained the Marine Predator Algorithm (MPA) for solving transcendental nonlinear equations in a MLI for eliminating the SHE. Using a three-phase, eleven-level MLI with a CHB architecture, the optimal switching angle values from MPA were used to eliminate the low-order harmonics and control the fundamental component for all modulation index values between 0 and 1. The simulation's outcomes demonstrated that the MPA algorithm outperforms competing algorithms in terms of accuracy and efficiency. Using experimental data from the Si-MOSFET, the thermal model of PLECS was used to calculate the conduction and switching losses, respectively. Here, the MPA technique was used to measure output power and losses at various modulation index values. This algorithm showed promising results, but its relatively high computational and memory requirements may limit its scalability for very high-level MLIs.

2.2 Problem Definition

The advantages and limitations of existing methods for the SHE in the CHB-MLI are given below. Paper [11] had the benefits of increased accuracy and convergence, reduced switching losses, and effectiveness in solving complex SHE problems; however, it also had the drawbacks included computational complexity, parameter tuning, implementation complexity, and the possibility of local optima trapping, although an insignificant one. This indicates that while swarm intelligence methods are powerful, their dependence on control parameters can make practical implementation more difficult. The teaching-learning-based optimization method, as used in [12], provides advantages like parameter independence and simplicity,

but it could also be sensitive to starting conditions and computationally demanding. This suggests that TLBO is better suited for controlled environments with well-defined operating ranges. Paper [13] introduces a SHE-PWM technique that offers the benefit of improved harmonic control and lower THD, but it could be computationally demanding and sensitive. The reliance on precise switching angle determination makes this method vulnerable when operating conditions fluctuate. The hybrid method used in [14] had the drawbacks of being computationally demanding for higher-level inverters and maybe still requiring a solid initial deduction for the NR technique to converge efficiently. Thus, hybrid approaches are effective but may involve extra overhead in terms of implementation complexity. However, it could shorten the calculation time and additionally increase the SHE solution accuracy. Paper [15] used the Marine Predator Algorithm provided benefits including lower harmonic distortion and better output voltage quality, but it has drawbacks in terms of memory utilization and computational complexity. This makes MPA an excellent candidate for smaller or mid-scale systems, but less practical for large-scale CHB-MLIs without further optimization.

3. Proposed Methodology

Generally, a stepped output waveform that significantly approaches a sine wave is produced by converting DC power into AC power using an MLI of several voltage levels. This stepped nature helps approximate the sinusoidal waveform without the need for extremely high switching frequencies, which in turn reduces switching losses. Still, the MLI had the problems of improved complexity, difficult component count, and potential voltage unbalancing. Thus, the model proposed a novel cascaded H-bridge MLI with the use of flying capacitors and diodes for better overall performance of the model. This hybrid topology leverages the advantages of cascaded structures for modularity, while incorporating passive components to stabilize voltage and reduce imbalance. Nevertheless, these topologies have a very low output voltage that is half of the supplied DC input. Similarly, individual switches are less stressed when series cascading is used. This reduction in voltage stress on individual devices improves reliability and extends the operational lifetime of the switches. Moreover, the electromagnetic interference and noise levels have been significantly decreased. By raising the operating frequency, these inverters' efficiency can be further improved. In the suggested model, the 11-level H-bridges model is cascaded, and each has its own DC supply, making it a type of multilevel inverter. Therefore, five sources are needed for an 11-level inverter. Such a configuration strikes a balance between waveform quality and hardware complexity, making it practical for medium-scale applications. The type of inverter is symmetrical. A stepped output with different DC levels is produced by adding the different DC output levels. Both positive and negative cycles have the same number of levels. After creating a pulsing DC with a diode bridge rectifier, ripples are eliminated using a filter circuit. This ensures that the DC input supplied to each H-bridge is stable, thereby improving the consistency of the AC output. To diminish THD and eliminate certain harmonics while maintaining the intended fundamental voltage, the inverter's switching angles are optimized in this model using a hybrid optimization approach called CS-WOA. Fig. 1 shows the generalized structure of a cascaded H-bridge multilevel inverter.

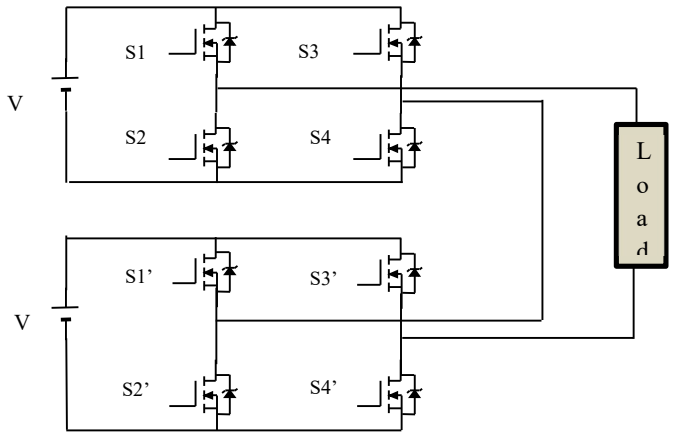


Fig. 1. *Generalized structure of cascaded H-bridge multilevel inverter*

The model could reduce k-1 harmonics for an N-level 3-phase CHBMLI with h-bridge cells. The following is a representation of the SHE equations, which include important and certain low-order non-triplet errors:

$$V_1 = \frac{4V_{dc}}{\pi}\left(\cos(\phi_1) + \cos(\phi_2) + \cos(\phi_3).....\cos(\phi_k)\right) \tag{1}$$

$$0 = \frac{4V_{dc}}{n\pi}\left(\cos(n\phi_1) + \cos(n\phi_2) + \cos(n\phi_3).....\cos(n\phi_k)\right) \tag{2}$$

The MI express the fundamental moduleis expressed in Eq. (3):

$$\cos(\phi_1) + \cos(\phi_2) + \cos(\phi_3).....\cos(\phi_k) = kMI = m_a \tag{3}$$

where,

$$MI = \frac{V_1}{\frac{4V_{dc}}{\pi}} = \frac{V_1}{V_{\max}} = \frac{V_1}{\frac{4kV_{dc}}{\pi}} = \frac{m_a}{k} \tag{4}$$

Where, V_1 denoted the basic phase voltage that the H-bridge produced. $V_{\max}$ signifies the maximum number of phase voltages attained by CHBMLI. $V_{\max}$ is gained while all the switching angles are zero,

$$V_{\max} = \frac{4kV_{dc}}{\pi} \tag{5}$$

With the use of a denoted objective function, the switching angles are calculated

$$f = \min\left[\left|100\frac{U_d - U_1}{U_d}\right|^4 + \sum_{S=5}^{S}\frac{1}{h_S}\left|50\frac{U_{hS}}{U_1}\right|^2\right] \tag{6}$$

where h_S signifies the harmonic direction. U_1 specify the rate of fundamental voltage, and U_d is the desired fundamental voltage. Additionally, the fitness function's second element is acceptable at a power of two in order to limit the undesired lower-order harmonics to less than 2%.

3.1 Hybrid Optimization Algorithm for CHB-MLI

The proposed CHB-MLI-based model used an original hybrid optimization algorithm termed CS-WOA, which interconnects the CSA and WOA methods, to minimize Total Harmonic Distortion (THD) and eliminate specific harmonics, though preserving the desired fundamental voltage. The hybridization leverages the global exploration strength of CSA with the exploitation efficiency of WOA, resulting in a more balanced and reliable optimization process.

A naturally inspired meta-heuristic program called WOA [9] replicates humpback whale social behavior. According to MWO, the exponential decay function over the iterations is provided as

$$a = 2\left(1 - \frac{m}{n}\right) \tag{7}$$

where m denotes the maximum number of iterations and n represents the current iteration. Investigation and manipulation use 60% and 40% of iterations, respectively. This division ensures that the algorithm spends sufficient time exploring the search space before intensifying its search around the best solutions.

In this paper, WO with a chaotic search approach is used to increase search efficiency and decrease the likelihood of becoming stuck at local optima. According to its definition, the chaotic equation is

$$x_{j+1} = \mu.x_j(1 - x_j) \tag{8}$$

The local search of chaos is defined as

$$cx_j^{n+1} = \mu.cx_j^n(1 - cx_j^n) \tag{9}$$

where cx_j^n denotes the variable of chaos, x_j is a variable, μ signifies the control parameter n signifies the iteration number. The integration of chaos theory helps diversify the search space, which prevents premature convergence and enhances robustness.

The WOA may have poor convergence speed and premature convergence while tackling complicated optimization issues. In order to get over these drawbacks, the model combined aWOA with the Cuckoo Search algorithm to produce the hybrid optimization algorithm. The enhancement of exploration, exploitation, and overall performance of the model is the important goal of this hybridization. In other words, CSA contributes strong global search diversity, while WOA ensures fine-tuning in the later stages, thus improving both accuracy and speed. To address the SHE problem and determine the best switching angles and further lower THD, the CS-WOA is developed in this study.

For CSA, the host birds find other eggs and destroy them to the next phase. The suitability of the nests in that location is demonstrated by the developed eggs. The more eggs that live in a given location, the better the advantage to that area. Therefore, CSA [10] will optimize the phrase that has the highest egg survival rate. They then go to this ideal habitat. A variation of ϕ radians is also present, and each cuckoo

only flies λ% of the total distance toward its ultimate destination (the goal habitat). Cuckoos can search a greater number of locations in any environment with the help of these two factors, λ and ϕ. The following definitions of' λ and ϕ apply to each cuckoo:

$$\lambda \sim U(0,1) \tag{10}$$

$$\phi \sim U(-\omega,\omega) \tag{11}$$

Where $\lambda \sim U(0,1)$ means that λ is a constantly distributed random number 0among 0 and 1. ω is the parameter that causes the habitat to deviate from the planned trajectory. Each mature cuckoo receives some eggs when all of the cuckoos have arrived at their final destination and new habitats have been chosen. An ELR is then computed for each cuckoo, taking into consideration the quantity of eggs distributed to each bird. The process of laying fresh eggs then begins anew. The switching angles of CHB-MLI are variables in relation to the SHE concept. This cyclical behavior mirrors natural evolution, ensuring continuous refinement of candidate solutions.

Thus, the two algorithms, such as CSA and WOA, are combined for the CHB-MLI to improve the overall performance of the selective harmonic elimination process in CHB-MLI. The outcome is an optimization framework that delivers lower THD, faster convergence, and improved adaptability under fluctuating input voltages.

4. Result and Discussion

The efficiency of the new hybrid CS-WOA optimization method for CHB-MLI is demonstrated in this section. A simulation framework was developed using MATLAB/Simulink 2021b to analyze the model's performance. Existing CSA and WOA techniques are compared with the proposed hybrid CS-WOA technique. To assess how well CS-WOA generates the greatest results, the performance of the CSA and WOA is compared to the proposed algorithm. The hybrid CS-WOA algorithm is used in the suggested scenario to carry out the CHB-MLI. By considering both convergence speed and harmonic suppression, the CS-WOA provides a comprehensive evaluation against the benchmark algorithms.

The model's outcome validates the hybrid CS-WOA technique, which outperforms alternative methods. More efficiently than existing methods, the proposed CS-WOA eliminates the selected harmonic in the CHB-MLI. This superiority can be attributed to the hybrid algorithm's ability to avoid premature convergence and effectively balance global exploration with local exploitation.

4.1. Simulation Outcomes for proposed CS-WOA-based CHB-MLI

For nine-level inverters with identical DC sources, the increment size of 0.01 and the MI range of 0 < MI ≤ 1. As illustrated in Fig. 2, the optimal switching angles are denoted by the ϕ_1, ϕ_2, ϕ_3, and ϕ_4. A nine-level CHBMLI with a 75V DC power source linked to every cell is replicated in Simulink in order to complete the simulation. In this model, 300V is the highest voltage that MLI can produce. This ensures that the output voltage profile is symmetric and sufficiently high to represent realistic inverter operation. Harmonic analysis is achieved using the FFT tool to examine how the obtained switching angles affect the THD.

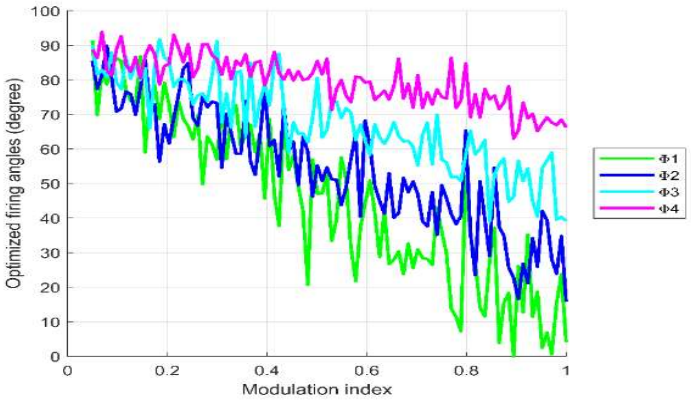
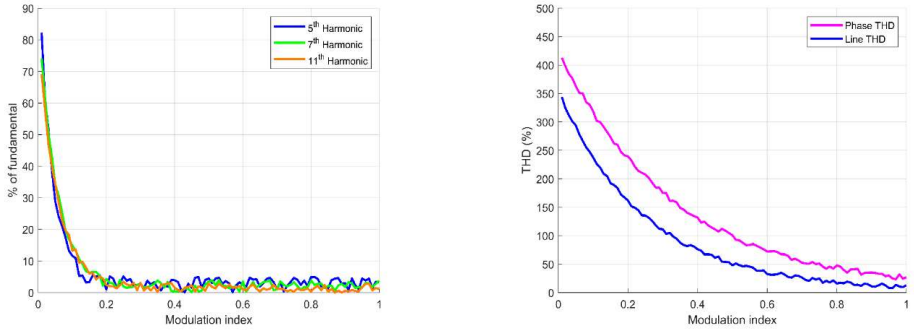


Fig. 2. *Switching angles under different modulation indices was optimized*

Fig. 3 displays the impact of the attained switching angles on the THD and removed harmonics. Fig. 3 (a) demonstrates that, for MI ranges of 0.1 to 0.2, the targeted harmonics were not removed, but their amplitude is negligible it suggesting that they have been removed. This confirms that even though the

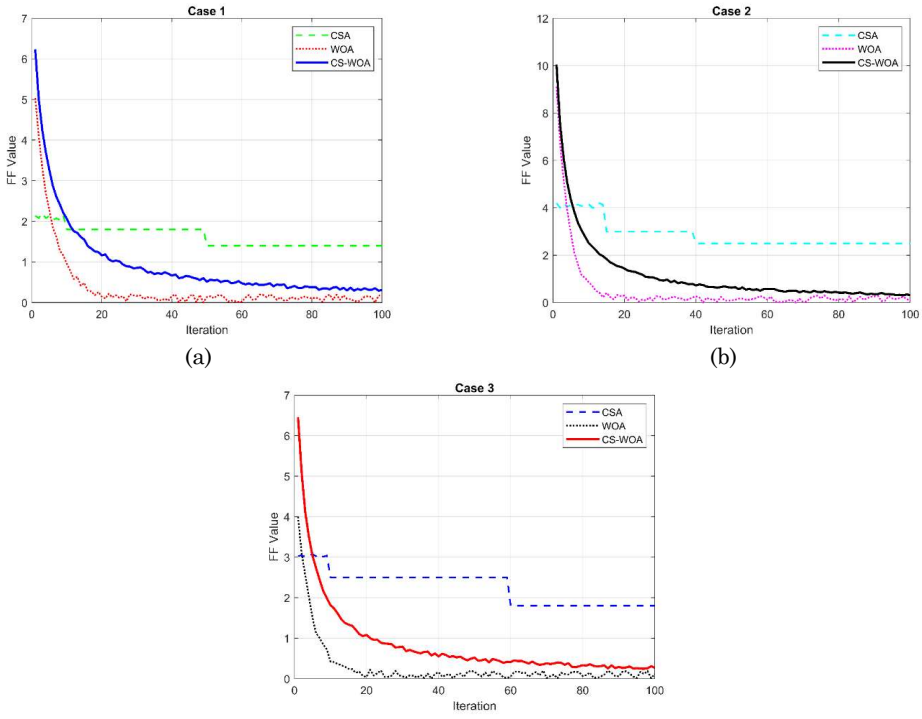
harmonic elimination is not explicit at very low MI values, the distortion contribution remains insignificant and within acceptable limits.



(a) (b)

Fig. 3. *Harmonics and THD under various MI(a) Harmonics removed as a percentage under different modulation indices(b) THD under various modulation indexes*

The experimental line voltage values at (a) MI=0.4, (b) MI=0.5, and (c) MI=0.6 are displayed in Fig. 4. SHEPWM. The line voltage waveforms obtained clearly demonstrate the staircase-like output, which closely resembles the sinusoidal waveform as MI increases. The computed THD and the algorithms' convergence behavior are the two main goals of the comparison analysis. Two additional algorithms, CSA and WOA, are compared to the suggested algorithm. It displays the convergence graphs for the different modulation indexes. These graphs reveal that the CS-WOA consistently converges faster to the minimum fitness value, thereby reducing computational effort. The suggested hybrid algorithm has achieved a lower fitness value than CSA and WOA across a wide range of modulation index, indicating its superior accuracy, as can be seen from the convergence graphs.



(a) (b)

(c)

Fig. 4. *Convergence Analysis (a) MI=0.4(b) MI=0.5 and (c) MI=0.6*

Furthermore, compared to CSA and WOA, it has reached the ideal answer with fewer iterations. This efficiency is particularly advantageous for real-time applications, where fast convergence is critical. Table 1 shows that all methods achieved the same THD values for a few modulation index values. The THD achieved by the suggested hybrid algorithm is lower than that of CSA and WOA at modulation index values of 0.4, 0.5, and 0.6, correspondingly.

Table 1. *THD Comparison between different algorithms*

Modulation Index	THD		
	CSA	WOA	CS-WOA
0.3	18.9	19.7	18.1
0.4	13.1	13	13.05
0.5	9.1	9	8.95
0.6	8.2	8.7	8
0.63	7.4	7.35	7.3
0.7	8.1	8	7.7
0.8	6.1	6.05	6
0.81	5	5.4	4.8

5. Conclusion

A novel hybrid optimization algorithm was suggested as a solution to the SHE equations for eliminating distortions in a CHB-MLI. The primary advantage of this approach lies in its ability to maintain the desired fundamental voltage while selectively suppressing low-order harmonics that typically degrade inverter performance. Using a three-phase, 11-level CHB-MLI experimental prototype based on the CS-WOA-based model's simulation and the efficacy of the suggested method was evaluated. For various modulation indexes, the proposed CS-WOA-based model exhibited better results than traditional CSA and WOA. This improvement demonstrates that hybridization of metaheuristic algorithms provides a more robust optimization landscape, ensuring adaptability across a wide MI range. The simulation outcomes show that the suggested CS-WOA algorithm produced a higher accuracy rate as compared to the existing CSA and WOA-based model for SHE of MLI. Moreover, the experimental validation confirmed that the algorithm is not only effective in simulations but also practical in real hardware implementation. This model attained reduced THD and speed of convergence. The multi-criteria search-based CS and WOA's accuracy was finally confirmed by the results for a CHB-MLI. Future research will probably focus on creating algorithms that are more reliable and computationally efficient, investigating novel hybrid strategies, and expanding the use of SHE to other applications.

Compliance with Ethical Standards

Conflicts of interest: Authors declared that they have no conflict of interest.

Human participants: The conducted research follows the ethical standards and the authors ensured that they have not conducted any studies with human participants or animals.

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