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Comparative Performance Evaluation of Conventional and Optimized Control Strategies for A Single-Phase 23-Level Multilevel Inverter

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Abstract: In this paper, the comparative performance analysis of conventional control and optimization-based control strategy of reduced-switch single phase 23-level multilevel inverter (MLI) is presented. The proposed inverter uses an asymmetrical DC-source configuration and uses only 10 power semiconductor switches to obtain the output voltage of 23 levels. Conventional Nearest Level Control with Pulse Width Modulation (NLC–PWM), Harris Hawks Optimization algorithm based Selective Harmonic Elimination (HHO–SHE) and Mother Optimization algorithm based Selective Harmonic Elimination (MOA–SHE) three control strategies are studied under the same operating conditions. Finally, simulations are performed in MATLAB/Simulink to analyse the output voltage, harmonic spectrum, total harmonic distortion (THD), and computing performance. The simulation results show that the proposed NLC–PWM strategy has the best performance and results in the lowest voltage THD value (0.230%) and the lowest current THD value (0.086%) with the simplest implementation and also the lowest computational complexity. Compared with the other optimization-based techniques, MOA–SHE offers the lower voltage THD, which is 0.816% and 1.119% with MOA–SHE and HHO–SHE, respectively, showing its superior capability for solving the switching-angle optimization problem. The obtained results prove the effectiveness of the proposed 23-level inverter topology and indicate that NLC–PWM is the most suitable method of inverter topology for applications, which demand high power quality and simple implementation, while MOA–SHE is an effective optimization-based application of SHE.

Keywords: Multilevel inverter, Selective Harmonic Elimination (SHE), Nearest Level Control (NLC), Harris Hawks Optimization (HHO), Mother Optimization Algorithm (MOA), Total Harmonic Distortion (THD).

1. Introduction

The rising share of renewable energy, electric vehicles, smart power grids, and medium-voltage industrial drives has brought about a high need for efficient power conversion systems. Multilevel Inverters (MLIs) have emerged as one of the promising power electronic converters due to their high-quality output voltage with reduced THD, lower electromagnetic interference (EMI), reduced voltage stress on semiconductor devices, and high efficiency. An MLI generates staircase voltage waveforms which are close to sinusoidal signals, and hence can be used directly in renewable energy integration, motor drives, flexible AC transmission systems (FACTS), high voltage direct current (HVDC) transmission, and other medium and high-power applications where conventional two-level inverters are unsuitable due to the higher voltage ratings required for the individual switches [1], [2].

Although conventional MLI topologies have these benefits, they still face several problems when the number of output voltage levels is raised. In general, the higher the voltage level the more power semiconductors switches, isolated DC sources, gate drivers and passive components are needed, increasing the converter size, implementation cost,

control complexity, reduction in reliability and switching and conduction losses [2]. Because of this, there has been a great deal of research on the design of reduced switch MLI topologies with a high number of voltage levels with minimal numbers of components [3]. The 23-level single-phase multilevel inverter used in this study has an asymmetrical DC-link with one 28 V source and five 56 V voltage sections, with the number of voltage-levels being a good compromise with a reduced number of power switches.

In addition to topology, the control strategy used has a tremendous impact on the quality of the output voltage, harmonic output, switching frequency, switching losses and computation complexity [4]. Several methods of modulation have been proposed such as PWM, NLC, Space Vector Modulation (SVM), Model Predictive Control (MPC) and Selective Harmonic Elimination (SHE) [5], [6]. Compared to SHE, NLC has low switching frequency and can effectively suppress the low-order harmonics by adjusting the switching angles with the desired fundamental output voltage, while NLC has low computation burden and simple implementation which can be applied to high-level MLIs [7], [8].

Optimal determination of switching angles for this nonlinear harmonic elimination problem has yet been further improved by recent metaheuristic optimization algorithms, which now make use of SHE. The Application of Algorithms like Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Grey Wolf Optimizer (GWO), HHO, Whale Optimization Algorithm (WOA) and recently MOA has shown promising performance in terms of better harmonic suppression and power quality [9], [10]. Most of the previous works have concentrated on the comparison of optimization algorithms used to solve the SHE problem or optimization of only one of the control strategies separately [11], [12], [13]. Few studies have been conducted to compare optimization-based SHE strategies with traditional control strategies under the same operating conditions and same topology of an MLI. Also, the use of MOA for the SHE switching angle optimization problem is still relatively under-explored for the case of MLIs [9], [14], [15].

The identified research gap motivated this paper wherein a comparative performance study of a conventional NLC–PWM strategy and two optimization-based SHE strategies based on HHO and MOA are carried out for a single phase 23-level multilevel inverter. All strategies are executed under the same operating conditions and their performances are compared in terms of output voltage quality, harmonic spectrum, THD, switching characteristics and convergence performance. Finally, effectiveness of the proposed MOA-based SHE strategy is validated by comparing with the HHO–based SHE and conventional NLC–PWM strategies [16], [17].

2. Literature Review

The rapid growth of multilevel inverters has fueled research to develop several topologies that have low number of switching components and high output voltage quality. Current research attention has been paid to reduce the number of power semiconductor switches, DC power sources and gate drivers while maintaining the number of output voltage levels. The reduced-switch topologies have shown increased efficiency, less implementation cost, and a simpler hardware complexity, which are good for renewable energy and medium-voltage applications [3], [18].

Various control strategies have been explored in order to enhance the performance of the MLIs. Various conventional methods like PWM, NLC, SVM and MPC have been widely used owing to their features to control the output voltage and suppress the harmonic distortion. Of these, NLC has been widely used for processing high level harmonics MLIs in use due to its simplicity and low computation load, and SHE has received much attention for its ability to remove any selected low order harmonics at low switching frequency [4], [5], [8].

Recently, metaheuristic optimization algorithms have proved to be successful in solving nonlinear SHE switching-angle optimization problem. GA, PSO, GWO, HHO and WOA algorithms have been successfully used to find optimum switching angle, which leads to reduction of THD and enhancement of output voltage quality. In most of the previous research works, however, the comparison has been made in between optimization algorithms or improvement of a single optimization-based control strategy [17], [19].

From the literature reviewed, little work has been done to compare conventional real-time control strategies with optimization based SHE strategies in the same reduced-switch MLI topology with the same operating conditions. Hence, this paper compares the performance of a conventional NLC–PWM strategy with the HHO based SHE strategy and the proposed MOA based SHE strategy to gain a complete analysis of the harmonic performance and quality of the output voltage.

3. Proposed Single-Phase 23-Level Multilevel Inverter

This part shows the proposed reduced switch single phase 23 level multilevel inverter used in this work. The proposed topology aims at achieving a staircase output voltage with high quality and minimum number of power semiconductor switches and hardware complexity. The next few subsections detail its working principle, voltage level generation process and switching states.

3.1 Topology description

The proposed single-phase 23-level multilevel inverter consists of an asymmetrical DC-link, ten power semiconductor switches (S1 to S10) and an RL load. The asymmetrical DC-link consists of one DC source rated at V_{dc} and five identical voltage sections rated at $2V_{dc}$, where $V_{dc} = 28\,\mathrm{V}$. This configuration will give you a maximum output voltage of about $11V_{dc}$ and will save you the need for 23 power components to create a staircase output voltage.

Switching network is divided into three functional groups. The switches S1 and S2 are the primary path-selection switches which are used to switch the current flow depending on the output voltage polarity requirement. The voltage-level selection network is composed of the switches S3, S4, S7, S8, S9 and S10; they can be activated only one at a time to select the proper voltage tap from the asymmetrical DC-link. Finally, switches S5 and S6 constitute the output switching stage, which switches the conduction path of the output to give the positive and negative voltage levels for the required staircase sequence. By using these three switching groups, the inverter can generate twenty-three voltage levels $(0, \pm, V_{dc}, \pm, 2V_{dc} \ldots \pm 11V_{dc})$, while the number of switches used is less than the topologies used in conventional multilevel inverters [3], [18].

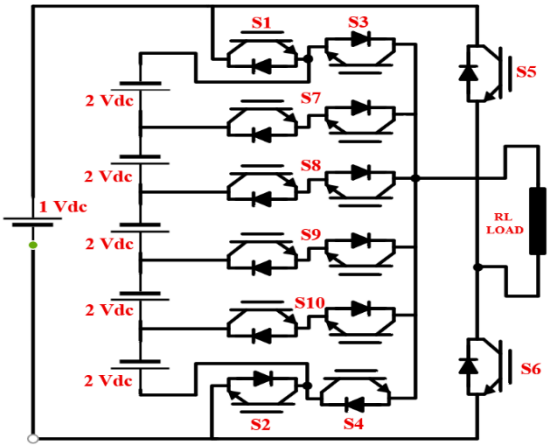


Figure 1. Proposed single-phase 23-level multilevel inverter

3.2 Operating principle

The proposed inverter utilizes the output voltage synthesis by choosing a suitable combination of the asymmetrical DC-link voltage segments, depending on the switching states presented in Table 1. There are 5 voltage sections of $2V_{dc}$ and one voltage source of V_{dc}, so the output voltage is stepped. There are 11 positive levels, 11 negative levels and 1 level of zero. The output voltage is therefore given in terms of

$$V_o = mV_{dc} \tag{1}$$

where $m = 0, \pm1, \pm2, \ldots, \pm11$. The sequential application of these switching states generates a symmetrical 23-level staircase waveform.

Table 1. Switching States of the Proposed Single-Phase 23-Level Multilevel Inverter.

level	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
1	1	0	1	0	0	1	0	0	0	0
2	1	0	0	0	1	0	1	0	0	0
3	1	0	0	0	0	1	1	0	0	0

4	1	0	0	0	1	0	0	1	0	0
5	1	0	0	0	0	1	0	1	0	0
6	1	0	0	0	1	0	0	0	1	0
7	1	0	0	0	0	1	0	0	1	0
8	1	0	0	0	1	0	0	0	0	1
9	1	0	0	0	0	1	0	0	0	1
10	1	0	0	1	1	0	0	0	0	0
11	1	0	0	1	0	1	0	0	0	0
0	1	0	0	0	1	0	0	0	0	0
-1	0	1	0	1	1	0	0	0	0	0
-2	0	1	0	0	0	1	0	0	0	1
-3	0	1	0	0	1	0	0	0	0	1
-4	0	1	0	0	0	1	0	0	1	0
-5	0	1	0	0	1	0	0	0	1	0
-6	0	1	0	0	0	1	0	1	0	0
-7	0	1	0	0	1	0	0	1	0	0
-8	0	1	0	0	0	1	1	0	0	0
-9	0	1	0	0	1	0	1	0	0	0
-10	0	1	1	0	0	1	0	0	0	0
-11	0	1	1	0	1	0	0	0	0	0

Table 1 presents the switching states for generating the 23 output voltage levels. The same switching sequence is used for all control strategies, whereas only the switching instants are determined by the selected control method.

4. Conventional NlC–PWM Control Strategy

The first control strategy explored in this work is the traditional NLC along with PWM. This strategy is chosen as the reference method because of its simple implementation, low computational complexity and it is commonly used in high level multilevel inverters. The main idea of NLC and PWM is to choose the voltage level which is the nearest to the instantaneous reference voltage and to attain the better output voltage waveform quality and lower harmonic distortion, respectively [4].

4.1 Nearest Level Control

The output voltage is produced by NLC using the voltage level in the available voltage levels which is closest to the reference voltage. NLC easily can be applied and has a low computation complexity, which is the reason why it is widely used in high level multilevel inverters [1].

The normalized reference voltage is calculated as

$$k = \text{round}\left(\frac{V_{ref}}{V_{dc}}\right), \; -11 \le k \le 11 \tag{2}$$

V_{ref} is the instantaneous reference voltage and V_{dc} is the voltage step between two successive output voltage levels. The level index k is then obtained from Table 1, which is then used to determine the corresponding switching state. An implementation of the NLC algorithm as a MATLAB/Simulink subsystem and its combination with a PWM stage is carried out in this work for enhancing the output waveform quality and harmonic distortion.

Unlike the traditional NLC, the proposed NLC–PWM algorithm introduces a PWM stage to compute the switching instants in the voltage range selected. This alteration enhances the smoothness of the output voltage wave form and helps to reduce the harmonics while maintaining the low computational complexity of NLC strategy [20].

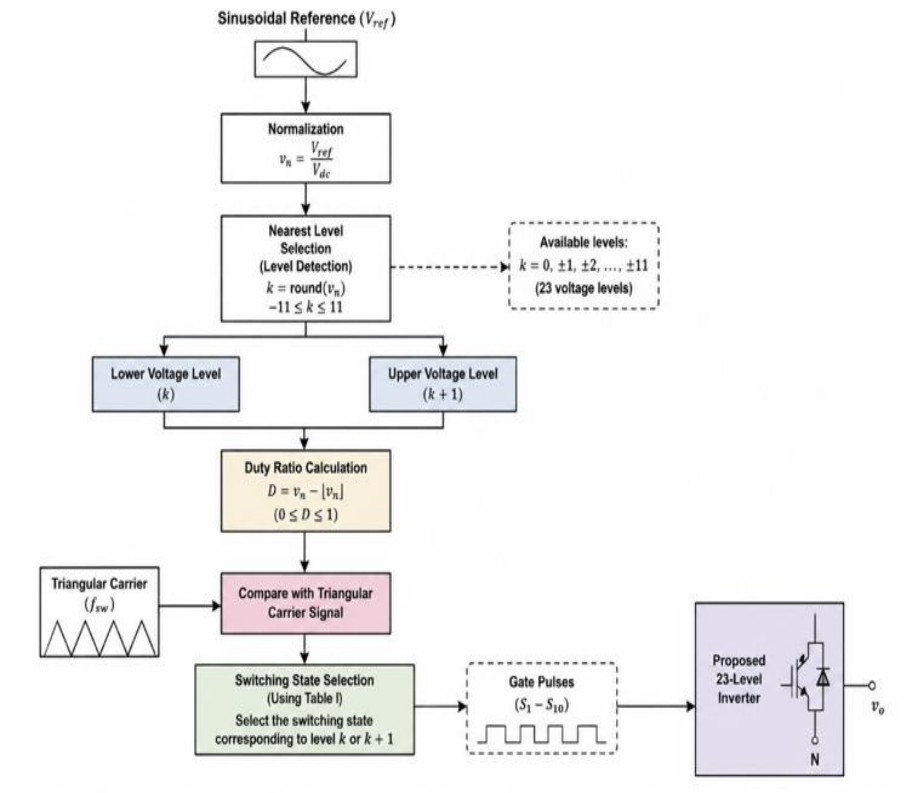


Figure 2. Block diagram of the proposed NLC–PWM control strategy.

4.2. HHO-Based SHE Control Strategy

SHE is used to compute the best switching angles to obtain the desired fundamental output voltage with the suppression of the selected low order harmonics. Because of the quarter-wave symmetry of the inverter output voltage, the DC component and even-order harmonics are automatically removed and only odd-order harmonics are considered. Hence the voltage output of the proposed 23 level inverter can be represented by the Fourier series as [21].

$$V_o(\omega t) = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{dc}}{n\pi} \left(\sum_{i=1}^{11} cos\,(n\theta_i) \right) sin\,(n\omega t) \tag{3}$$

where V_{dc} is the basic DC voltage, n is the harmonic order, and θ_i denotes the switching angles satisfying:

$$0 < \theta_1 < \theta_2 < \cdots < \theta_{11} < \frac{\pi}{2} \tag{4}$$

The fundamental component and minimization of the selected odd harmonics, are optimized for the desired fundamental voltage, with switching angles set. The optimization problem is stated as follows:

$$J = (V_1^* - V_1)^2 + \sum_{n=3,5,7,\ldots,21} \left(\frac{V_n}{V_1} \right)^2 \tag{5}$$

The desired fundamental voltage is denoted as V_1^* and the fundamental component obtained is V_1; the amplitude of the n^{th} harmonic is denoted as the amplitude of V_n. The goal of the optimization process is to keep the fundamental voltage the same as before the optimization and to minimize the selected low-order odd harmonics, which will minimize the total harmonic distortion [22].

The nonlinear optimization problem defined in (5) is solved by the HHO algorithm. In this method, the eleven switching angles are represented by each hawk, which is a candidate solution. The stopping criterion is used to stop the process of iteratively updating the population, which is done by both exploration and exploitation steps. Optimal switching-angle set provided by HHO is then employed to produce the gate signals of the proposed 23-level inverter [19].

4.3. MOA-Based SHE Control Strategy

MOA [17] is then used to solve the same SHE optimization problem to further investigate the effectiveness of recent metaheuristic optimization techniques. Each search agent in the same way as in the HHO-based approach corresponds to a set of feasible switching angles that satisfy the constraints in Section 5. The goal is to find the best switching-angle combination to maintain the desired fundamental voltage whilst reducing the desired harmonic components to a minimum.

Initially, the population of candidate solutions is randomly generated as:

$$X_i = [\theta_1, \theta_2, \dots, \theta_{11}] \tag{6}$$

where X_i denotes the i^{th} candidate solution.

During each iteration, the candidate solutions are updated according to the mother-guidance mechanism as:

$$X_i^{new} = X_i + r(X_{best} - X_i) \tag{7}$$

where X_{best} is the best solution obtained so far and r is a uniformly distributed random number within the interval $[0, 1]$.

To enhance the search capability and avoid premature convergence, the updated solution is expressed as:

$$X_i^{new} = X_{best} + \alpha(X_i - X_{best}) \tag{8}$$

where α is an adaptive learning coefficient controlling the balance between exploration and exploitation [17]. The optimization step is repeated until the stopping condition is met. The best set of switching angles found with MOA is then applied to create the gate signals for the proposed 23-level inverter [23].

5. SHE Optimization Problem Formulation

The overall optimization procedure used for both HHO–SHE and MOA–SHE strategies is shown in Figure 3. The optimization algorithms use the same objective function and mathematical formulation for SHE: SHE mathematical formulation is same, and objective function is same. The optimization process begins by generating an initial population of switching-angle candidates, then goes through an iterative process of updating and evaluating the population until a convergence criterion is met.

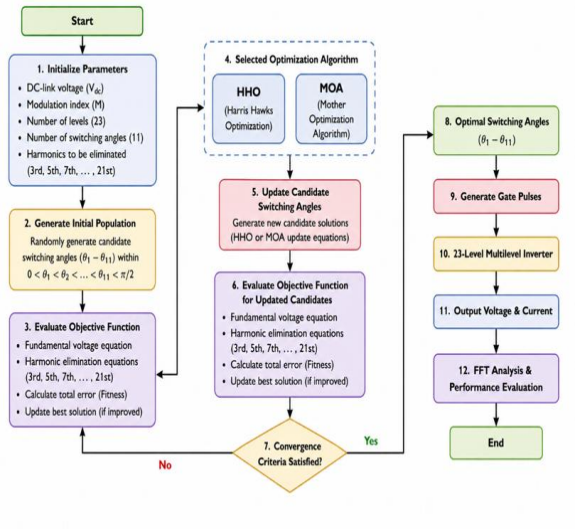


Figure 3. General flowchart of the proposed HHO–SHE and MOA–SHE optimization strategies.

Based on the Fourier series analysis [21], the SHE optimization problem is formulated as follows:

$$b_1 = \frac{4V_{dc}}{\pi}[\cos 1\,\theta_1 + \cos 1\,\theta_2 + \cdots + \cos 1\,\theta_{11}] = V1 \tag{9}$$

$$b_3 = \frac{4V_{dc}}{3\pi}[\cos 3\,\theta_1 + \cos 3\,\theta_2 + \cdots + \cos 3\,\theta_{11}] = 0 \tag{10}$$

$$b_5 = \frac{4V_{dc}}{5\pi}[\cos 5\theta_1 + \cos 5\theta_2 + \cdots + \cos 5\theta_{11}] = 0 \quad (11)$$

$$b_7 = \frac{4V_{dc}}{7\pi}[\cos 7\theta_1 + \cos 7\theta_2 + \cdots + \cos 7\theta_{11}] = 0 \quad (12)$$

$$b_9 = \frac{4V_{dc}}{9\pi}[\cos 9\theta_1 + \cos 9\theta_2 + \cdots + \cos 9\theta_{11}] = 0 \quad (13)$$

$$b_{11} = \frac{4V_{dc}}{11\pi}[\cos 11\theta_1 + \cos 11\theta_2 + \cdots + \cos 11\theta_{11}] = 0 \quad (14)$$

$$b_{13} = \frac{4V_{dc}}{13\pi}[\cos 13\theta_1 + \cos 13\theta_2 + \cdots + \cos 13\theta_{11}] = 0 \quad (15)$$

$$b_{15} = \frac{4V_{dc}}{15\pi}[\cos 15\theta_1 + \cos 15\theta_2 + \cdots + \cos 15\theta_{11}] = 0 \quad (16)$$

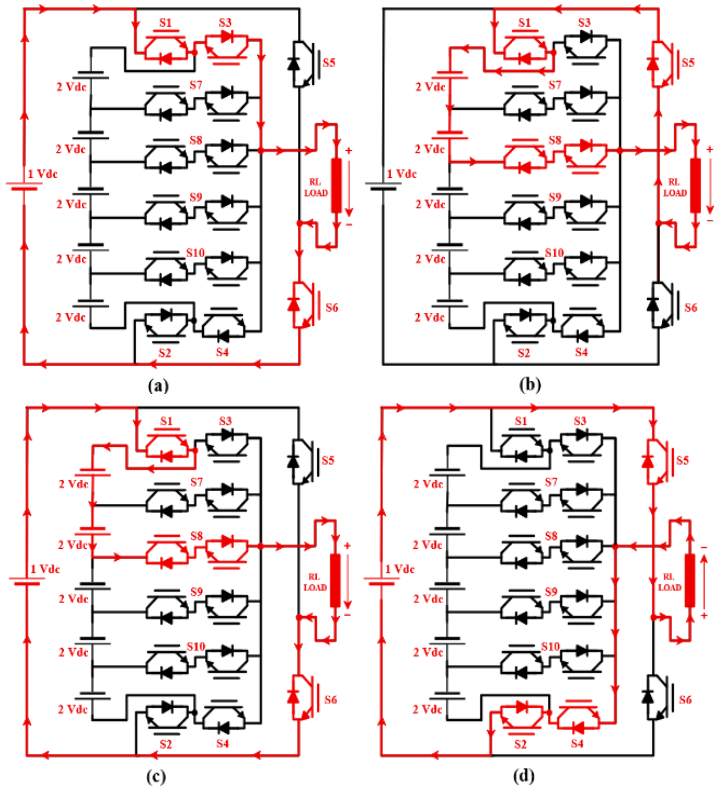
$$b_{17} = \frac{4V_{dc}}{17\pi}[\cos 17\theta_1 + \cos 17\theta_2 + \cdots + \cos 17\theta_{11}] = 0 \quad (17)$$

$$b_{19} = \frac{4V_{dc}}{19\pi}[\cos 19\theta_1 + \cos 19\theta_2 + \cdots + \cos 19\theta_{11}] = 0 \quad (18)$$

$$b_{21} = \frac{4V_{dc}}{21\pi}[\cos 21\theta_1 + \cos 21\theta_2 + \cdots + \cos 21\theta_{11}] = 0 \quad (19)$$

The above equations constitute the SHE optimization problem which both of the HHO and MOA algorithms attempt to solve. The optimal switching angles obtained are then used to produce the gate pulses for the proposed 23 level multilevel inverter.

To further clarify the operating principle of the proposed 23-level inverter, selected switching states and their corresponding current conduction paths are illustrated in Fig. 4. The highlighted paths indicate the conducting switches and DC sources involved in synthesizing the required output voltage levels. These representative operating modes demonstrate how different combinations of the power switches and asymmetrical DC sources are utilized to generate the multilevel output waveform.



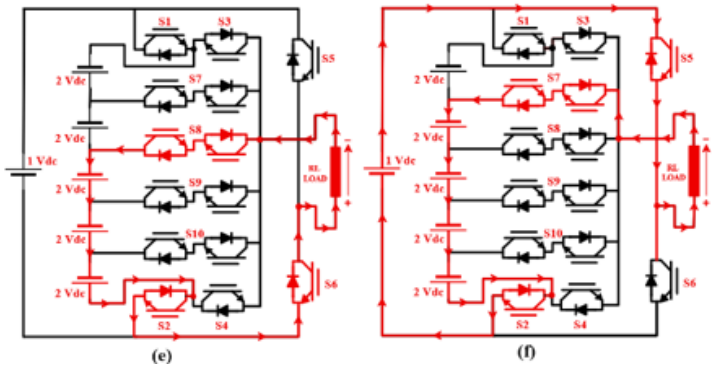


Figure 4. Switching states for selected output voltage levels: (a) V_{dc}, (b) $4V_{dc}$, (c) $5V_{dc}$, (d) $-V_{dc}$, (e) $-6V_{dc}$, and (f) $-9V_{dc}$.

6. Results And Discussion

Comparative simulations are extensively performed in the MATLAB/Simulink R2024a with the proposed single-phase 23-level multilevel inverter for evaluating the effectiveness of the suggested control strategies under similar operating conditions. In order to achieve a fair comparison with the above, the three control strategies namely NLC–PWM, HHO–SHE and MOA–SHE was implemented, and the performance was evaluated with the same inverter topology, load parameter and DC voltage configuration. The output voltage waveform, the harmonic spectrum, the THD, the switching characteristics, the convergence of the optimization algorithms, and the computational efficiency are the aspects of the performance investigated.

6.1 Results of the NLC–PWM Strategy

The simulation results of the proposed 23-level multilevel inverter with the conventional NLC–PWM control strategy are shown in figure 5. The output voltage is a clearly stepped staircase as depicted in Fig. 5(a) and is very close to the sinusoidal reference, while the load current is almost sinusoidal in nature due to the RL load. Under the selected operating conditions, the output voltage is about 307.53 V and the load current is about 14.67 A. The results show that the output waveform can be generated with low THD by the use of the conventional NLC–PWM method using the proposed inverter.

The normalized harmonic spectra corresponding to these are shown in Fig. 6(b). Based on the FFT analysis, the proposed inverter has a voltage THD of 0.23% and current THD of 0.086% showing excellent harmonic performance. The Fundamental is the dominant harmonic and the lower order harmonics are suppressed to an acceptable level. These results confirm the voltage tracking accuracy and the satisfactory power quality of the NLC–PWM strategy, which constitutes a suitable reference for comparison with the voltage tracking control strategies of HHO–SHE and MOA–SHE proposed in the following sections.

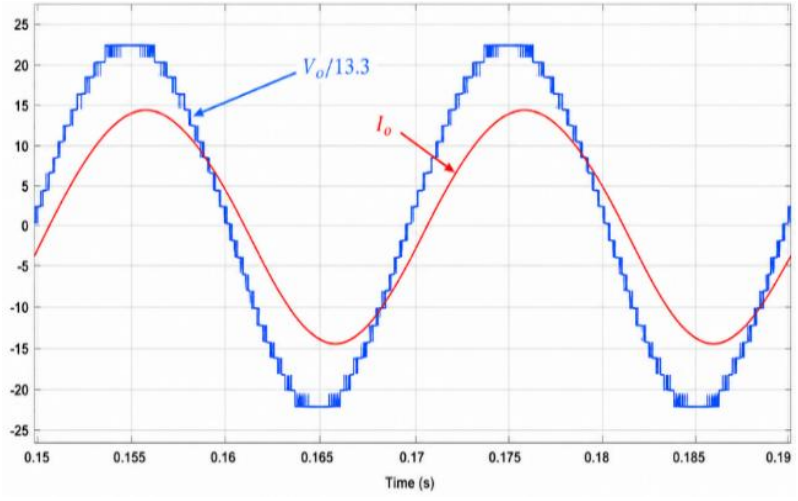
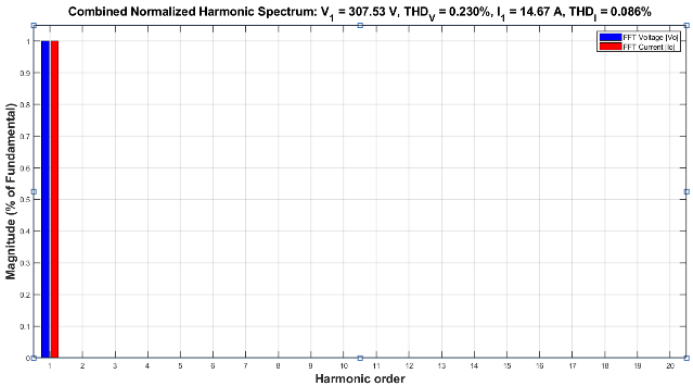
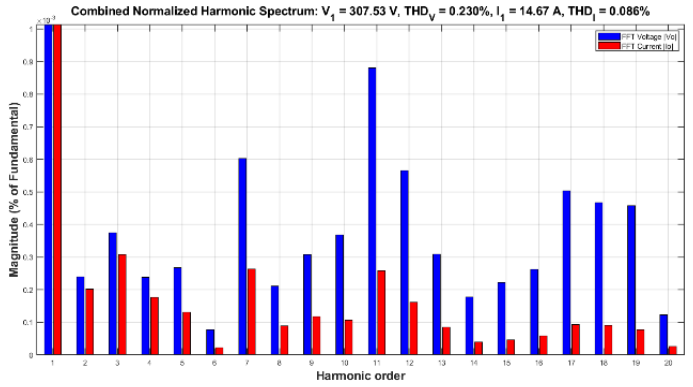


Figure 5. Output voltage and load current waveforms of the proposed 23-level inverter using the NLC–PWM control strategy.



(a)



(b)

Figure 6. Normalized voltage and current harmonic spectra of the proposed 23-level inverter using the NLC–PWM control strategy: (a) complete FFT spectrum and (b) zoomed harmonic spectrum.

6.2 Results of the HHO–SHE Strategy

The simulation results of the proposed 23-level multilevel inverter using the HHO–SHE controls strategy are presented in Fig. 7. The output voltage is a well-defined staircase in the form of a 23-level voltage as illustrated in Fig 8(a), where the switching angles are controlled by the Harris Hawks Optimization algorithm. The output is fairly close to the desired sinusoidal pattern and the load current is nearly sinusoidal, as the load is RL type. The fundamental output voltage obtained is 311.11 V and the load current is about 14.84 A, thus the effectiveness of the switching-angle optimized solution is proved.

The normalized harmonic spectra are shown in Fig. 7(b). The FFT analysis shows that the voltage THD for HHO-SHE is 1.119% and the current THD is 0.286%. Selected Low Order Harmonics are suppressed effectively with the required fundamental component. The results have shown that the HHO algorithm has an effective solution for the SHE optimization problem with less switching frequency and good output current quality, which is suitable to apply to the optimization problem of the multilevel inverter.

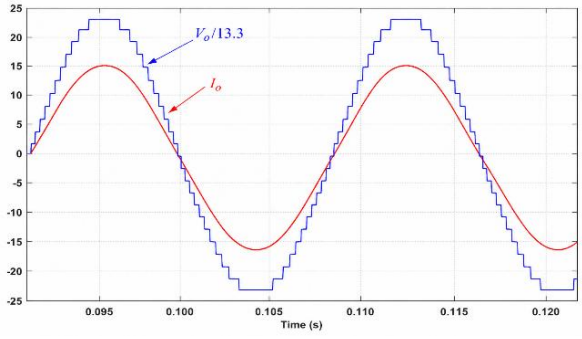
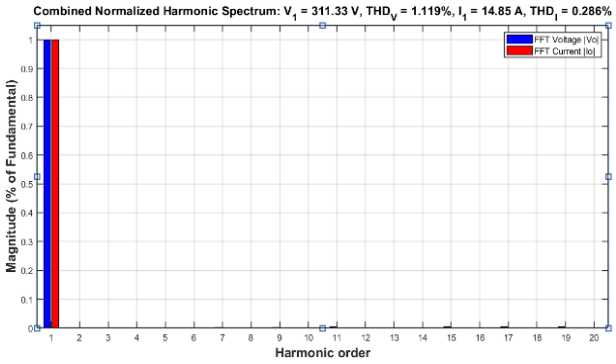
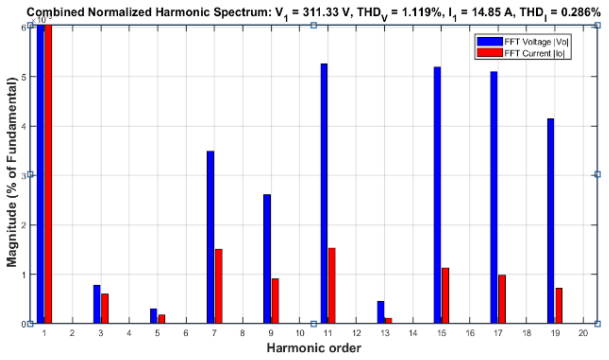


Figure 7. Output voltage and load current waveforms of the proposed 23-level inverter using the HHO–SHE control strategy.



(a)



(b)

Figure 8. Normalized voltage and current harmonic spectra of the proposed 23-level inverter using the HHO–SHE control strategy: (a) complete FFT spectrum and (b) zoomed harmonic spectrum.

6.3 Results of the MOA–SHE Strategy

The simulation results of the proposed 23-level multilevel inverter with the MOA–SHE controls strategy are shown in figure 9. The optimized switching angles (via the Mother Optimization Algorithm) produce a well-defined staircase output voltage, which is close to the desired sinusoidal output voltage, as demonstrated in Fig. 9(a). The RL load produces almost sinusoidal load current, which indicates the effectiveness of the optimal switching angle setting to obtain good output current shape. The value of fundamental output voltage obtained is 310.34V and the output load current is about 14.80A.

The normalized harmonic spectra are plotted in Fig. 10(b). The analysis results of the FFT show that the proposed MOA–SHE strategy is able to reach the voltage THD of 0.816% and the current THD of 0.209%, which demonstrates an excellent harmonic suppression potential. The MOA algorithm has a lower current harmonic distortion than the HHO–SHE strategy and gives an output voltage (fundamental) very close to the HHO–SHE strategy. The results show the high efficiency of the MOA algorithm in finding the optimum switching angles for the SHE problem, which improves the quality of the output current and increases the overall inverter performance.

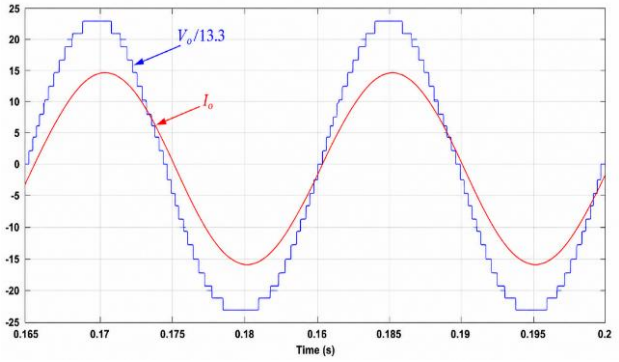
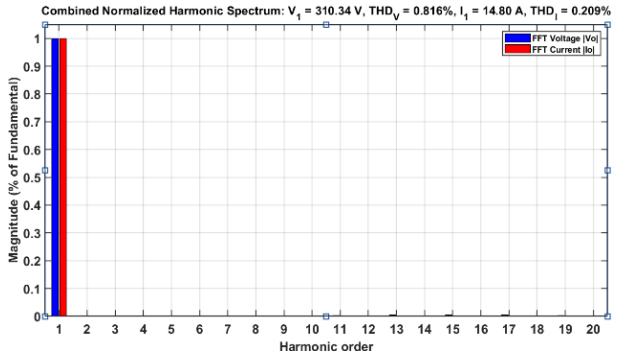
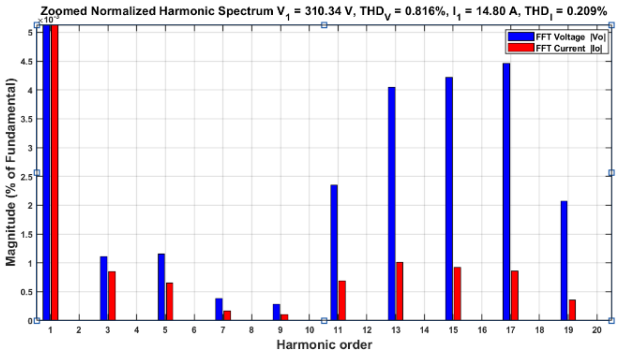


Figure 9. Output voltage and load current waveforms of the proposed 23-level inverter using the MOA–SHE control strategy.



(a)



(b)

Figure 10. Normalized voltage and current harmonic spectra of the proposed 23-level inverter using the MOA–SHE control strategy: (a) complete FFT spectrum and (b) zoomed harmonic spectrum.

Table 2. Optimal switching angles obtained using HHO and MOA for the proposed 23-level multilevel inverter.

Switching Angle	HHO (deg)	MOA (deg)
θ_1	3.9141	1.899
θ_2	6.7841	7.8356
θ_3	13.7047	13.8574
θ_4	18.0951	17.2781
θ_5	23.4927	25.0634
θ_6	31.0847	28.9811
θ_7	34.437	36.2349
θ_8	43.6017	42.6069
θ_9	49.2649	50.0101
θ_{10}	59.8274	59.3635
θ_{11}	72.2373	71.7011

6.4 Comparative Performance Analysis

The effectiveness of three investigated control strategies (NLC–PWM, HHO–SHE, and MOA–SHE) is summarized in Table 3. The comparison is done on the basis of basic output voltage, voltage THD, current THD, computational complexity and overall performance.

The simulation results suggest that the conventional NLC–PWM technique generates a fundamental output voltage of 307.53 V, a voltage THD of 0.230% and a current THD of 0.086%. The results show that the proposed NLC – PWM approach is capable of achieving the best harmonic performance among all considered approaches. Nearest level selection

and PWM in combination deliver very high output waveform quality with a simple implementation and very low computational complexity [20].

The selected low order harmonics are minimized using the optimized switching angles in HHO–SHE strategy and a fundamental output voltage of 311.11 V is obtained. Even though the obtained voltage THD (1.119%) and current THD (0.286%) are higher than what is obtained by the proposed NLC–PWM strategy, the results are still satisfactory. The performance of HHO is limited by the optimization process, it is able to solve the SHE optimization problem, but needs to perform a searching procedure offline before the inverter is turned on [14], [15].

In the same way, the MOA–SHE strategy provides a fundamental output voltage of 310.34 V, voltage THD of 0.816% and current THD of 0.209. The MOA algorithm has better harmonic suppression and lower THD values than HHO–SHE, which verifies that it has a better optimization capability than HHO–SHE. However, under the investigated operating conditions its harmonic performance is still worse than the proposed NLC–PWM strategy.

The NLC–PWM strategy as implemented is the simplest and most appropriate for real-time applications since there is no optimization process involved, and selects the closest voltage level. Compared to the two, both of the latter (HHO–SHE and MOA–SHE) require offline optimization to obtain the optimal switching angles, demanding more computation in the design phase. After achieving the optimum angles, however, both methods can be implemented online, with a relatively small amount of computation required, via a lookup table.

In conclusion, the comparison confirms that the proposed NLC–PWM control strategy allows to obtain the best overall performance, in terms of lowest voltage THD (0.230%), lowest current THD (0.086%), and lowest computational complexity. In comparison with other optimization techniques, the MOA–SHE technique presents lower voltage THD and current THD values, so it is the best optimization technique to solve the SHE problem. As the primary goal is to maximize power quality with simplicity of implementation, the proposed NLC–PWM strategy is found to be the best solution for the developed 23-level multilevel inverter.

Table 3. Performance comparison of the proposed 23-level multilevel inverter using different control strategies.

Method	V1	THDv (%)	THDi (%)	Comp.	Performance
NLC–PWM	307.53	0.23	0.086	Low	Best THDi
HHO–SHE	311.11	1.119	0.286	Med.	Good
MOA–SHE	310.34	0.816	0.209	Med.	Best optimized THDv

7. Conclusion

This paper compared the performance of proposed 23-level multilevel inverter under three different control strategies: conventional NLC–PWM, HHO–SHE and MOA–SHE. All strategies were executed and assessed under identical operating conditions and using MATLAB/Simulink. The simulation results revealed that the proposed inverter can produce high quality multilevel output voltage which is free from high order harmonic distortion.

The NLC–PWM method was the most successful of the investigated methods in terms of the lowest voltage THD (0.230%) and the lowest current THD (0.086%) and the lowest number of computational blocks and the simplest implementation. It can be seen that the MOA–SHE strategy is more effective than the HHO–SHE strategy with the voltage THD reduced to 0.816% while the HHO–SHE strategy results in a voltage THD of 1.119%, which indicates the better optimization performance of the MOA algorithm for solving the SHE switching-angle optimization problem.

Overall, the findings suggest that the proposed NLC–PWM strategy is the most appropriate solution if both high-power quality and low harmonic distortion are desired and simplicity of implementation is also required. At the same time, MOA–SHE is a competitive alternative that could be employed in SHE applications, and the optimization performance of MOA–SHE is better than HHO–SHE. Further work will be conducted using experimental validation and real-time implementation of the proposed inverter.

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