Mikailalsys Journal of
Advanced Engineering International

e-ISSN : 3046-9694
p-ISSN : 3046-8914

Index : Harvard, Boston, Sydney University, Dimensions, Lens, Scilit, Semantic, Google, etc

https://doi.org/10.58578/MJAEI.v2i2.6405

Harmonic Improvement in Single-Phase Multilevel Inverter Using a Hybrid of Artificial Bee Colony (ABC) and Firefly (FFA) Algorithms

Ibraheem Auwal[1], A. L. Amoo[2], A. Mohammed[3], Yakubu Barau Bal[4], D. M. Nazif[5]
[1,2,3]Abubakar Tafawa Balewa University Bauchi, Bauchi State, Nigeria;
[4,5]Federal Polytechnic Bauchi, Bauchi State, Nigeria
wlibraheem@gmail.com

Article Info:

Submitted:	Revised:	Accepted:	Published:
May 22, 2025	Jun 20, 2025	Jul 1, 2025	Jul 6, 2025

Abstract

Harmonic distortion presents a significant challenge in renewable energy integration, particularly in conventional 2-level inverters. Multilevel inverters, such as the cascaded H-bridge topology, offer an effective solution by generating multiple voltage levels, thereby reducing distortion and eliminating the need for bulky filters. This study investigates harmonic reduction in a single-phase 21-level asymmetric cascaded H-bridge multilevel inverter using a novel hybrid optimization algorithm combining Artificial Bee Colony (ABC) and Firefly Algorithm (FA). The hybrid ABC-FA algorithm is designed to determine optimal switching angles for minimizing Total Harmonic Distortion (THD) while addressing the limitations of conventional heuristic methods. Modeled and simulated in MATLAB/SIMULINK, the proposed algorithm demonstrates enhanced performance in both harmonic reduction and convergence speed. Simulation results show that the hybrid ABC-FA algorithm achieves THD levels below 5%, representing a 10–20% improvement over standalone ABC or FA implementations. Additionally, the algorithm exhibits faster convergence, highlighting its effectiveness and reliability for improving power quality and facilitating efficient integration of renewable energy sources into the electrical grid.

Keywords: Harmonics; Optimization; Artificial Bee Colony; Firefly Algorithm; MATLAB; Multilevel Inverter

INTRODUCTION

Population growth, industrialization, and technological advancements have increased global energy demand, leading to a shift towards renewable sources like solar and wind power. However, integrating these intermittent sources presents technical challenges (Blaabjerg *et al.*, 2017).

Power electronics, particularly inverters, are crucial for converting renewable energy into alternating current for grid integration or standalone power systems. However, traditional two-level inverters can cause high harmonic distortion, compromising power quality, system efficiency, and equipment damage (Rodriguez *et al.,* 2002).

To overcome these limitations, Multilevel Inverters **(**MLIs**)** have emerged as a viable solution. By generating output voltages using multiple discrete voltage levels, MLIs can synthesize waveforms with significantly reduced harmonic content. This results in improved power quality, increased system efficiency, lower switching losses, reduced electromagnetic interference (EMI), and enhanced fault tolerance (Rodriguez *et al.*, 2002). The performance of MLIs is highly dependent on the appropriate selection of switching angles, which control how the voltage levels are combined to produce the output waveform.

Optimal switching angle determination is a complex, nonlinear optimization problem. Nature-inspired metaheuristic algorithms such as the Artificial Bee Colony (ABC) algorithm and the Firefly (FA) algorithm have been applied individually in past studies for this purpose due to their ability to efficiently explore complex solution spaces and avoid local minima (Karaboga & Basturk, 2007; Yang, 2009). This study explores a hybrid ABC-FA optimization algorithm, which combines the strengths of the ABC algorithm and the FA algorithm for faster convergence and better accuracy in reducing harmonics in multilevel inverters, a technique that has gained popularity in solving complex engineering problems**.**

Single-phase multilevel inverters are crucial in modern power electronics for reducing harmonic distortion and improving power quality. However, achieving minimal harmonic content in the output voltage remains a challenge due to complex mathematical computations and ineffective solutions.

The effectiveness of harmonic mitigation in multilevel inverters is highly dependent on selecting precise switching angles. While various nature-inspired optimization algorithms—such as the Artificial Bee Colony (ABC) and Firefly (FA) algorithms—have promising techniques in this area, yet their individual application may still be limited by convergence speed or solution quality.

The study uses a hybrid ABC-FA optimization algorithm to optimize switching angles for harmonic reduction, enhancing convergence efficiency and solution accuracy, ultimately improving inverter performance and power quality.

Harmonic Distortion

Harmonic distortion occurs because the output waveform of a power electronics converter contains non-sinusoidal components, which deviate from the ideal sinusoidal waveform required for power systems. These harmonics, which are integer multiples of the

fundamental frequency, this can be attributed to the switching behavior of the power electronics of the inverter (Rodriguez *et al.*, 2002). Multi-level inverters (MLIs) generate multiple voltage levels, affecting the output waveform with harmonic components. Harmonic distortion severity is quantified using total harmonic distortion (THD), which represents the root-mean-square (RMS) value of the harmonic component to the fundamental component. Lower THD indicates a sinusoidal waveform with reduced distortion. Harmonics are classified based on frequency ratio.

Odd harmonics, generated by power electronic converters, can cause distortion and affect system performance. Triple harmonics, added to neutral conductors, can cause overheating and equipment damage, requiring special attention (Blaabjerg *et al.,* 2017). Harmonics can cause significant losses, reduced power factor, overheating, electronic device failure, and communication interference, necessitating the development of effective harmonic reduction technologies for stable power system operation.

Multilevel Inverter Topology and CHB-MLI Modeling

MLI topologies, including cascaded H-bridge-bridge, flying capacitor, and neutral point fixed, each have unique characteristics and advantages. CHB MLI is notable for its modular structure and scalability (Rodriguez *et al.*, 2002). The CHB (cascaded H-bridge) MLI (multilevel inverter) uses series H-bridge cells to generate three voltage levels, allowing for a step waveform with reduced harmonic content. Mathematical modeling helps understand its operation and design effective harmonic reduction strategies, allowing for analysis of harmonic distortion and optimization of coupling angles.

Efficient energy conversion in inverters depends on the topology and modulation type, with three basic topologies: DCMLI, CHBMLI, and FCMLI, enhancing energy sustainability. Figure 1 shows the classification of multilevel inverters.

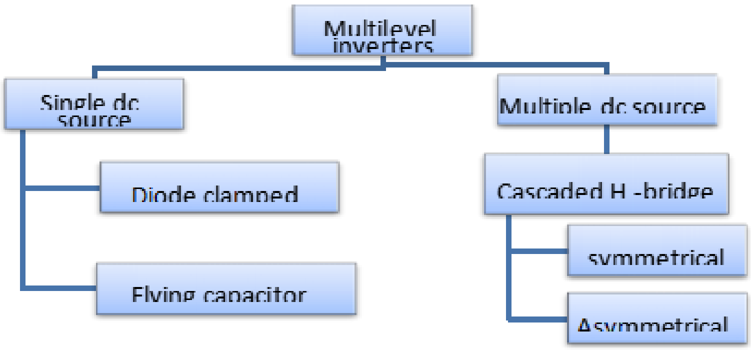


Figure 1: Classification of multilevel inverter based on topology (Kumar,2014)

Modulation Techniques

Almost all power electronic converters operate in switching mode where the power electronic switches are always in the ON or OFF position, and therefore, operating these devices in the linear region results in unwanted power losses (Djudzdo *et al.,* 2017). When semiconductor devices operate in switching mode, the switching transients due to the transistor turn-off time are a significant factor in switching power consumption (Jawanjal, 2017). To optimize power flow in a converter, switches must switch between ON and OFF states at a predetermined time, allowing energy storage devices to filter out harmonics. A switching frequency of at least 10 times higher is recommended (Prathiba & Renuga, 2010).

Pulse width modulation (PWM) is a process used to control the average value of a signal, suppressing harmonics. It can be classified into carrier-based and non-carrier-based techniques, with carrier-based PWM involving a high-frequency carrier signal, and non-carrier-based PWM manipulating the duty signal (Prabaharan & Palanisamy, 2017). Many multilevel converter applications are also focused on industrial medium and high voltage motor drives, grid interfaces for renewable energy systems, flexible AC transmission systems

(FACTS), and traction drive systems (Venkatakrishna et al., 2014). Figure 2 shows the modulation techniques of multilevel inverters.

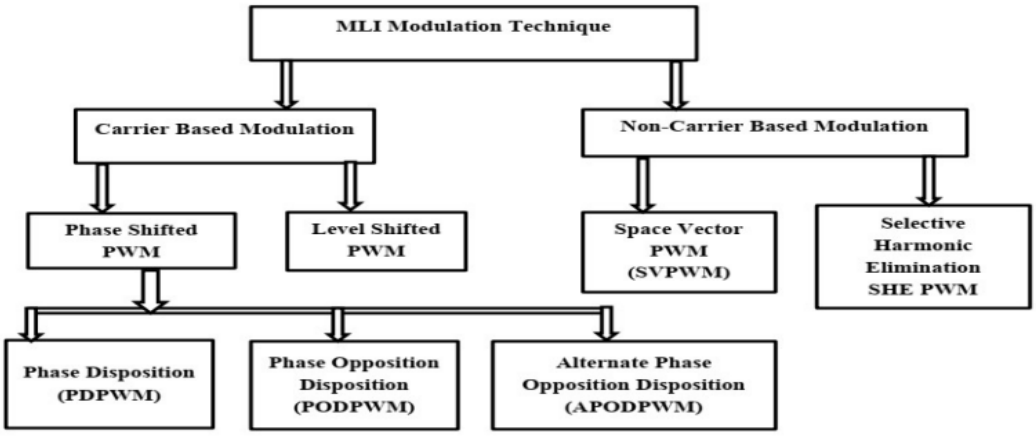


Figure 2: Multilevel Inverter modulation techniques (Diyoke & Onwuka, 2015)

MATERIALS AND METHODS

Materials

The primary tools of this study are software-based and utilize the capabilities of simulation and computer analysis. The materials are broken down in sequel.

Study area

The study uses computational and simulation methods to model and optimize a single-phase 21-level asymmetric cascaded H-bridge multilevel inverter, utilizing the MATLAB/SIMULINK environment for analysis and performance evaluation. Simulation environment in MATLAB/SIMULINK accurately represents switching behaviors, analyzes harmonics, and applies metaheuristic optimization algorithms, replicating realistic conditions in renewable energy applications, especially grid-tied systems.

Material used

In achieving the objectives of this research, the following materials were employed: Personal computer (PC), MATLAB/SIMULINK software.

Methodology

This research focuses on modeling, simulating, and analyzing a single-phase cascaded H-bridge multilevel inverter for harmonic reduction using a hybrid optimization approach. It formulates switching angles and develops a hybrid ABC-FA algorithm.

The hybrid ABC-FA algorithm optimizes switching angles to minimize Total Harmonic Distortion in output voltage waveforms. Its performance is evaluated for convergence speed, computational efficiency, and THD minimization. Simulations and validation against IEEE 519 standards assess the algorithm's robustness and suitability for practical inverter control applications.

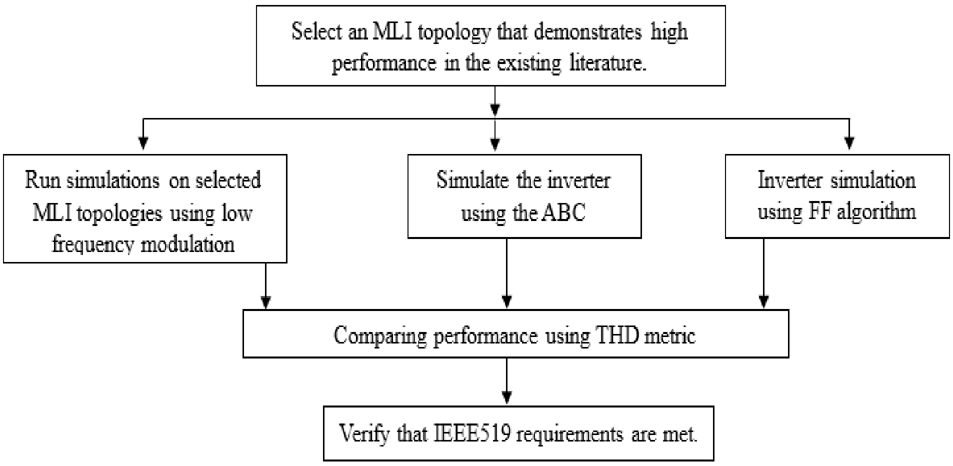


Figure 3: Research methodology flow

Problem formulation

The optimization of the total harmonic switching angle (THD) is formulated as a minimization problem, which can be expressed as:

Minimization: $\frac{1}{10m}[\cos\theta_1 + \cos\theta_2 + \cos\theta_3 + \cos\theta_4 + \cos\theta_5 + \cdots + \cos\theta_{10}]$ ... (1)

Where m is the modulation index, $\theta_1, \theta_2, \theta_3, \theta_4, \theta_5 \ldots \theta_{10}$ *are the switching angle*

Subject to the following constraints:

$$\cos 3\theta_1 + \cos 3\theta_2 + \cos 3\theta_3 + \cos 3\theta_4 + \cos 3\theta_5 + \cdots + \cos 3\theta_{10} = 0 \quad \ldots(2)$$

$$\cos 5\theta_1 + \cos 5\theta_2 + \cos 5\theta_3 + \cos 5\theta_4 + \cos 5\theta_5 + \cdots + \cos 5\theta_{10} = 0 \quad \ldots(3)$$

$$cos7\theta_1 + cos7\theta_2 + cos7\theta_3 + cos7\theta_4 + cos7\theta_5 + \cdots + cos7\theta_{10}=0 \quad \ldots(4)$$

$$cos9\theta_1 + cos9\theta_2 + cos9\theta_3 + cos9\theta_4 + cos9\theta_5 + \cdots + cos9\theta_{10} = 0 \quad \ldots(5)$$

$$cos11\theta_1 + cos11\theta_2 + cos11\theta_3 + cos11\theta_4 + cos7\theta_5 + \cdots + cos7\theta_{10} = 0 \quad \ldots(6)$$

$$cos13\theta_1 + cos13\theta_2 + cos13\theta_3 + cos13\theta_4 + cos13\theta_5 + \cdots + cos13\theta_{10} = 0 \quad \ldots(7)$$

$$cos15\theta_1 + cos15\theta_2 + cos15\theta_3 + cos15\theta_4 + cos15\theta_5 + \cdots + cos15\theta_{10} = 0 \quad \ldots(8)$$

$$cos17\theta_1 + cos17\theta_2 + cos17\theta_3 + cos17\theta_4 + cos17\theta_5 \ldots + cos17\theta_{10}=0 \quad \ldots(9)$$

$$cos19\theta_1 + cos19\theta_2 + cos19\theta_3 + cos19\theta_4 + cos19\theta_5 + \cdots + cos19\theta_{10} =0 \quad \ldots(10)$$

Where: $\theta_1 < \theta_2 < \theta_3 < \theta_4 < \theta_5 < \theta_6 < \theta_7 < \theta_8 < \theta_9 < \theta_{10} < \frac{\pi}{2}$ …(11)

Implementation of ABC algorithm

The Artificial Bee Colony (ABC) algorithm is implemented using the MATLAB software platform. The flow chart is shown in Figure 4.

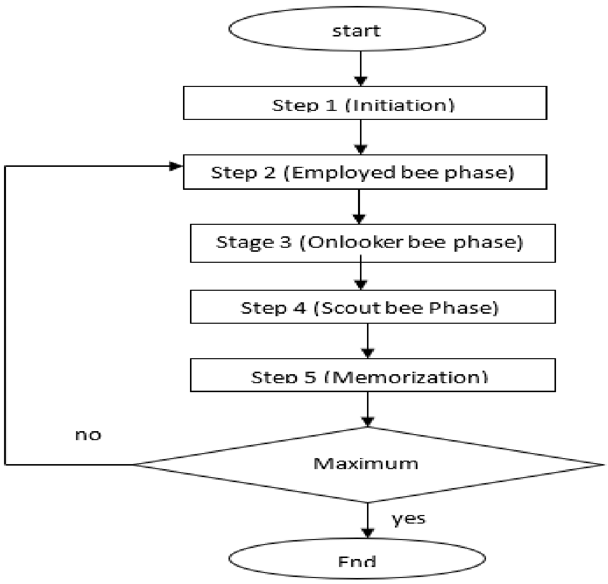


Figure 4: ABC flow chart

Firefly Algorithm Implementation

Step1 Initialization: initialize a population of fireflies with random switching angles within the feasible range: $\theta_1,\theta_2,\theta_3,\theta_4\theta_5,\ldots\theta_{10}$

Step2 Attractiveness: The attractiveness function is defined base on the distance between the switching angles, given by the formulae below:

$\theta_{ij} = \|\theta_i - \theta j\|$ ….(12)

where: $\theta_{i,}$ and θ_j are switching angles and

θ_{ij} is the distance between the switching angles i and j.

Step3 Movement: Update the positions (switching angles) of each switching based on the attractiveness of other switching angles and random movement.

$\theta_i^{t+1} = \theta_i^t + \beta_o \mathrm{e}^{-\gamma r_{ij}^2}\left(\theta_j^t - \theta_i^t\right) + \alpha_t \varepsilon_i^t$ …(13)

The switching angle i is attracted to another more attractive (brighter) switching angle j according to the eqen. (21)

Where: θ_i^{t+1} *is the position of the i − th switchin angle at time* t. β_o *is* attractiveness at distance 0. Y is the light absorption coefficient, α_t *is a randomization parameters.*

Step4 : Evaluate the fitness (THD) of each switching angle using the objective function below:

$\frac{1}{10}[\cos\theta_1 + \cos\theta_2 + \cos\theta_3 + \cos\theta_4 + \cos\theta_5 + \ldots + \cos\theta_{10}]$

Step5: Terminate the algorithm after a specified number of iterations when a convergence criterion is met.

Implementation of hybrid ABC-FA algorithms

The hybrid ABC-FA algorithm is implemented using the MATLAB software platform and the flow chart is shown in Figure 5.

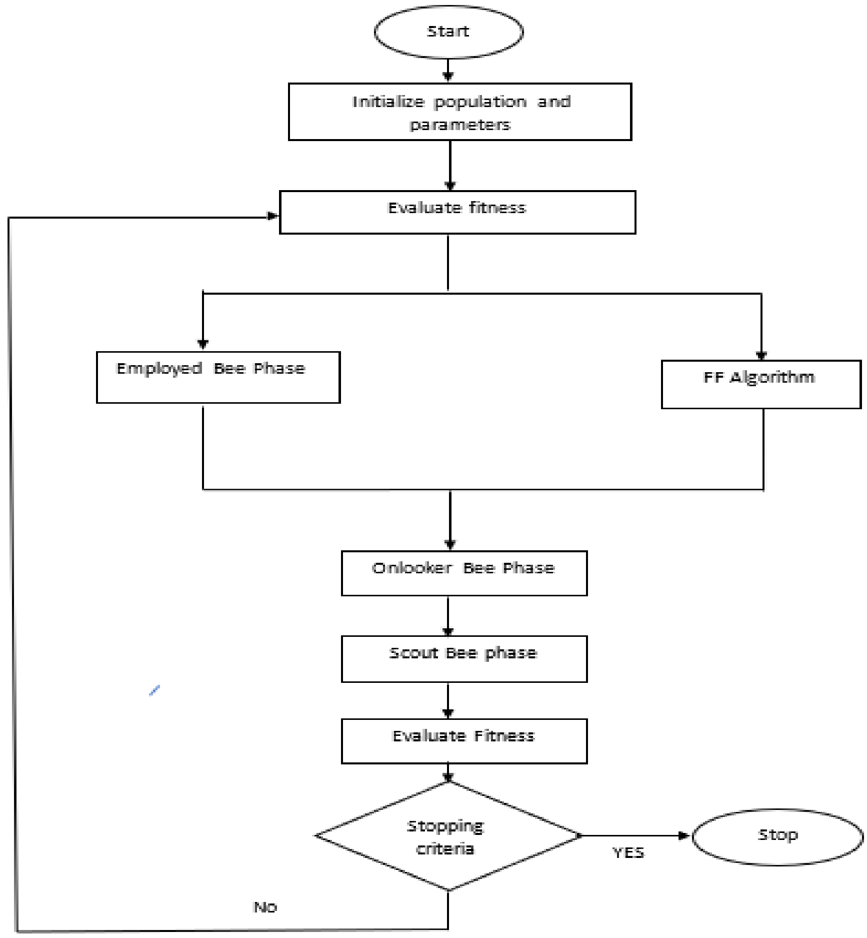


Figure 5: Hybrid ABC-FA algorithm Flowchart

Proposed Inverter Structure

The number of levels for a single-phase multilevel inverter is best selected based on the mathematical equations relating the number of DC sources to the inverter levels.

$$L=2s+1 \quad ...(14)$$

Where s is the number of individual DC sources. The proposed inverter structure is shown in Figure 6.

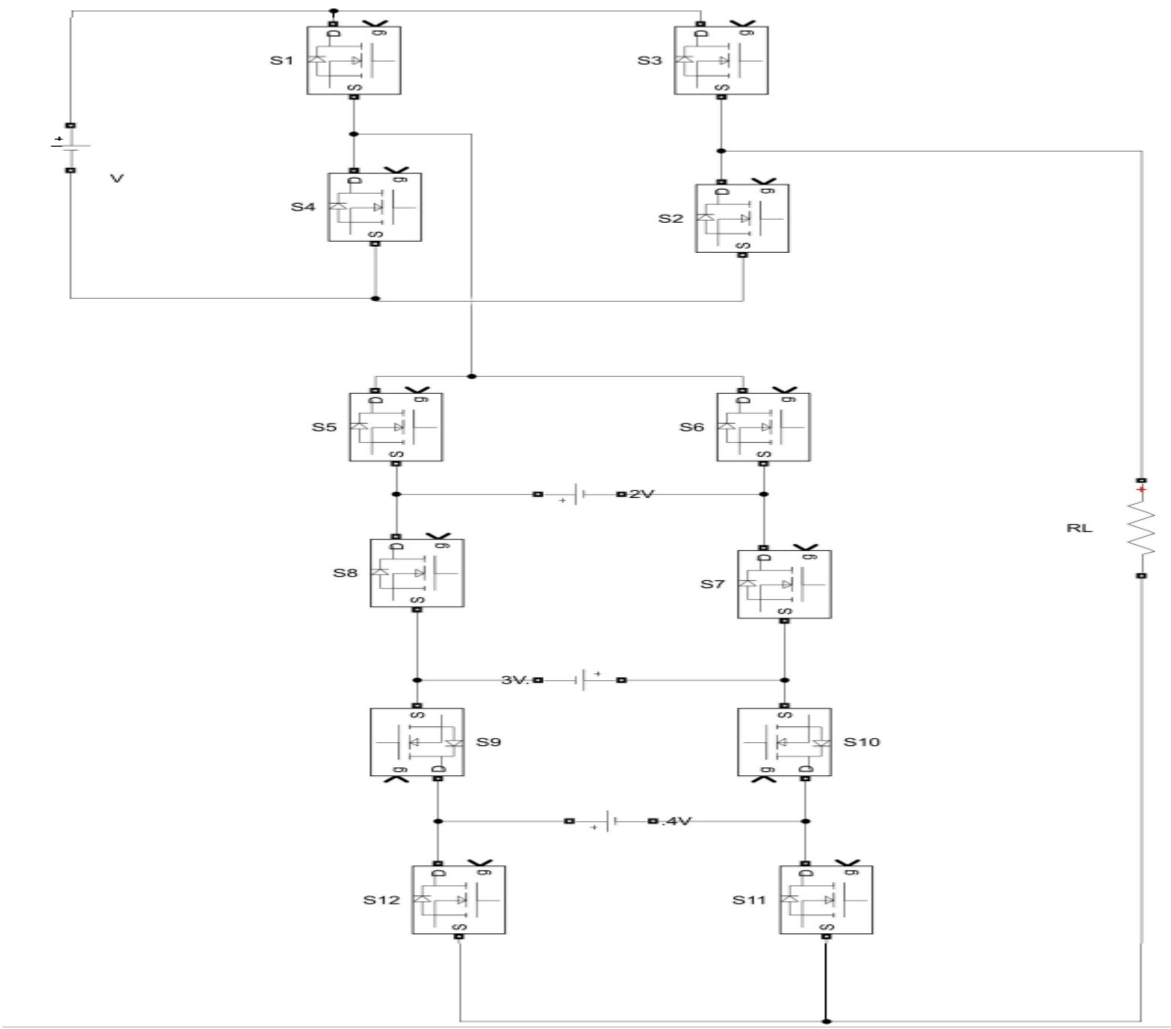


Figure 6: Proposed Multi-Level Inverter Topology

The circuit operates by activating diagonal switches to generate voltage sources V1, V2, V3, and V4. To generate V1 (Vdc), switches S3, S11, S10, S7, S6 and S4 must be turned ON. For V2 (2Vdc), switches S2, S12, S9, S8, S6 and S4 must be turned ON.

Table 1: Switching Table for Proposed 21 levels - Inverter

Voltage	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}	S_{12}
$10V_{dc}$	0	0	1	1	0	1	0	1	0	1	0	1
$9V_{dc}$	0	1	0	1	0	1	0	1	0	1	0	1
$8V_{dc}$	0	0	1	1	1	0	0	1	0	1	0	1
$7V_{dc}$	0	1	0	1	1	0	0	1	0	1	0	1
$6V_{dc}$	0	0	1	1	0	1	0	1	0	1	1	0
$5V_{dc}$	0	0	1	1	0	1	1	0	0	1	0	1
$4V_{dc}$	0	1	0	1	0	1	1	0	0	1	0	1
$3V_{dc}$	0	1	0	1	1	0	0	1	0	1	1	0
$2V_{dc}$	0	1	0	1	0	1	0	1	1	0	0	1
V_{dc}	0	0	1	1	0	1	1	0	0	1	1	0
0	0	1	0	1	0	1	1	0	0	1	1	0

Voltage	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}	S_{12}
$-V_{dc}$	1	1	0	0	0	1	1	0	0	1	1	0
$-2V_{dc}$	0	1	0	1	1	0	1	0	0	1	1	0
$-3V_{dc}$	0	1	0	1	0	1	1	0	1	0	0	1
$-4V_{dc}$	0	1	0	1	1	0	0	1	1	0	1	0
$-5V_{dc}$	1	1	0	0	1	0	0	1	1	0	1	0
$-6V_{dc}$	1	1	0	0	1	0	1	0	1	0	0	1
$-7V_{dc}$	0	1	0	1	0	1	1	0	1	0	1	0
$-8V_{dc}$	1	1	0	0	0	1	1	0	1	0	1	0
$-9V_{dc}$	0	1	0	1	1	0	1	0	1	0	1	0
$10V_{dc}$	1	1	0	0	1	0	1	0	1	0	1	0

Table 7 compares the proposed inverter structure with the existing topology for the same number of levels (n=21).

Table 2: Comparison of the Proposed Inverter and the Conventional Topology.

	21-level DCMLI	21-Lvel FCMLI	21-Level CHBMLI	Proposed Topology
Number of power Semiconductor Switches	40	40	40	12
Number of DC bus Capacitors	20	20	---	---
Number of Clamping Diodes	380	---	----	---
Number of DC sources	1	1	10	4
Total	441	61	50	16

Based on the comparison, the proposed topology offers several advantages: it is cheaper due to the reduced number of components, it is very compact due to the minimal heat dissipation measures required, and it is more efficient due to the elimination of the use of capacitors, which can often be a point of failure in electrical systems (Umar, 2019).

RESULTS AND DISCUSSIONS

Multilevel Inverter Output without Optimization

The inverter model was simulated without applying any optimization algorithm to observe the baseline output waveform and its harmonic profile. The output voltage waveform for the unoptimized switching angles and FFT plot are shown in Figures 7 and 8 respectively.

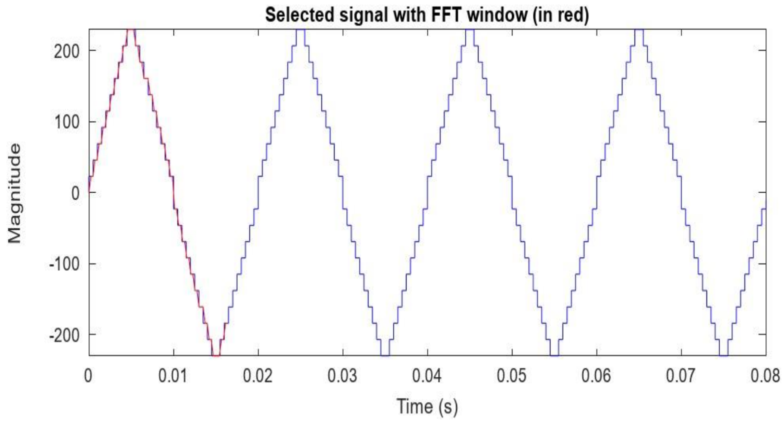


Figure 7: Output Voltage Waveform of 21-Level CHB-MLI Without Optimization

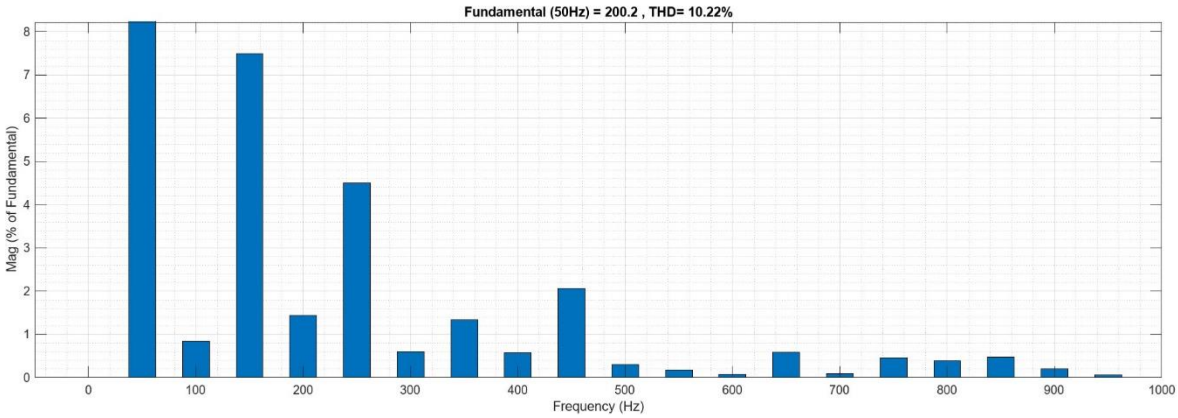


Figure 8: FFT Spectrum of Output Voltage Without Optimization

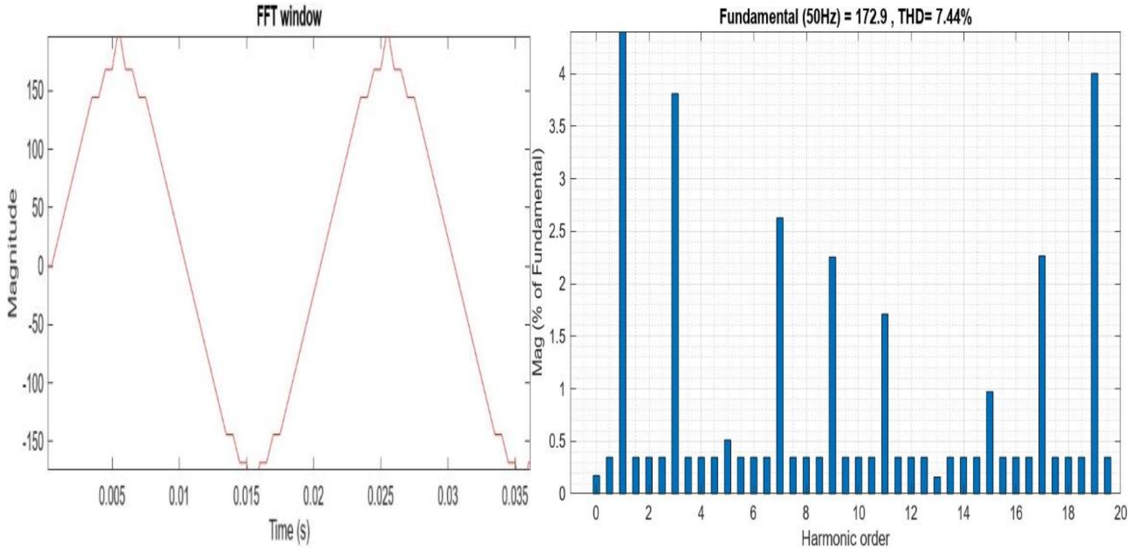
The FFT analysis of the unoptimized waveform yielded a THD of 10.22.67% for the fundamental voltage magnitude of 200.2 V. The THD obtained indicates the presence of harmonic components above the IEEE519 limits.

Optimization of Switching Angles

In this section, results from the application of the FF, ABC and hybrid ABC-FF algorithms for switching angle optimization are presented. The goal is to minimize THD by eliminating lower-order harmonics while maintaining a higher fundamental component.

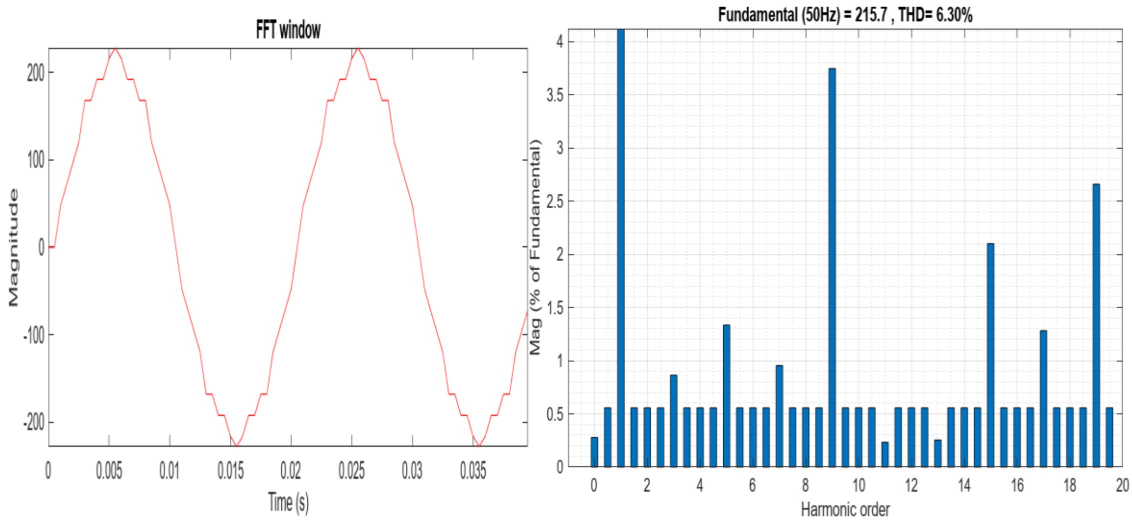
Firefly Algorithm for switching angles optimization

Figures 9 to 13 show the optimized switching angles for minimizing THD at modulation indices: 0.4, 0.6, 0.8, 1.0 and 1.2 respectively. Each Figure has been obtained using Firefly method and it minimizes THD depicting FFT window of the waveform in time domain as Figure (a) and spectrum plot for harmonic orders between fundamental (50 Hz) to 20th order harmonics of the output voltage as Figure (b).



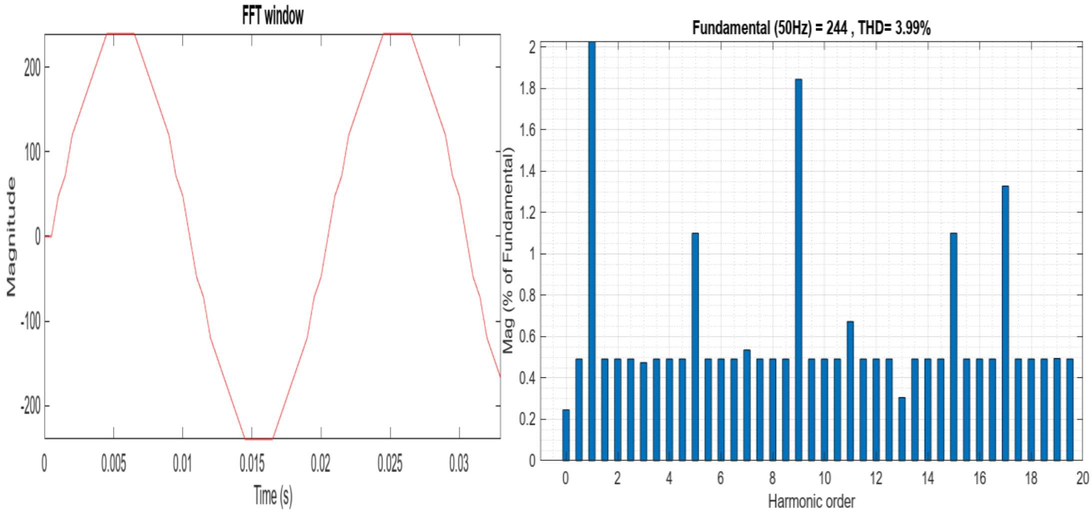
(a) (b)

Figure 9: A 21-Level CHB-MLI With FA at M_I: 0.4: (a) FFT window (b) Spectrum plot



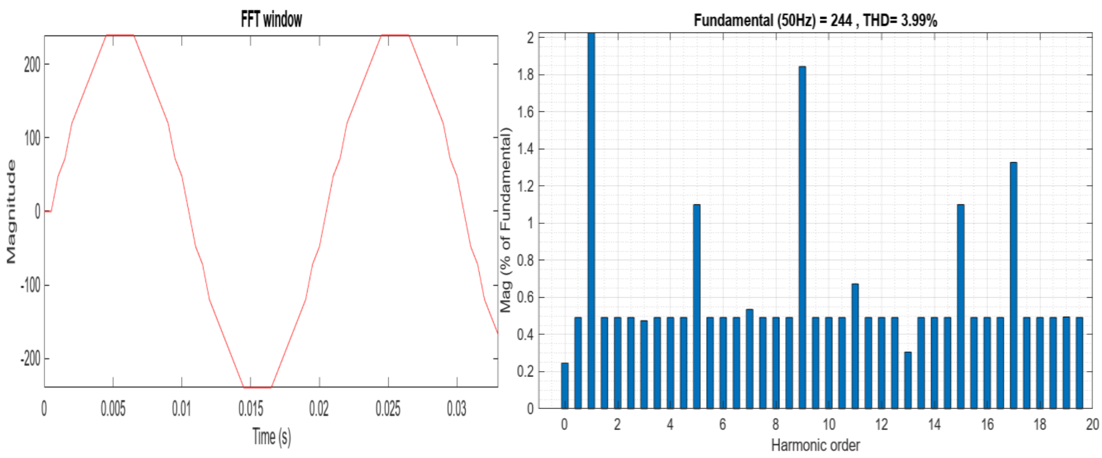
(a) (b)

Figure 10: A 21-Level CHB-MLI With FA at M_I: 0.6: (a) FFT window (b) Spectrum plot



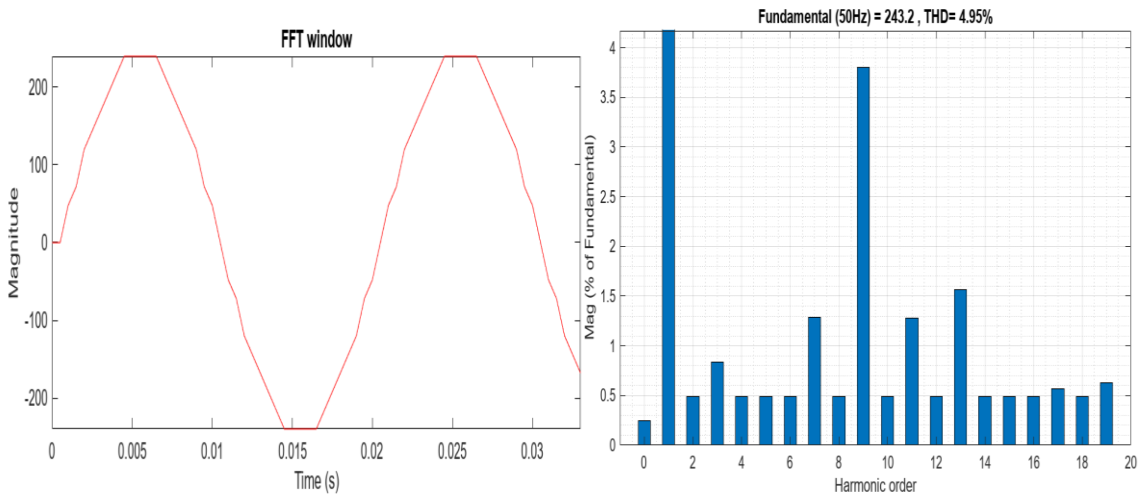
(a) (b)

Figure 112: A 21-Level CHB-MLI With FA at M_I: 0.8: (a) FFT window (b) Spectrum plot



(a) (b)

Figure 123: A 21-Level CHB-MLI With FA at M_I: 1.0: (a) FFT window (b) Spectrum plot

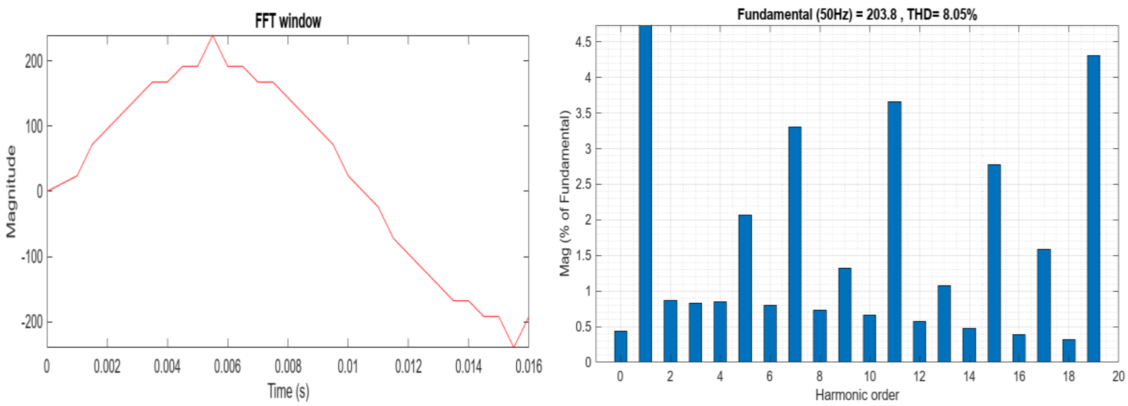


(a) (b)

Figure 134: A 21-Level CHB-MLI With FA at M_I: 1.2: (a) FFT window (b) Spectrum plot

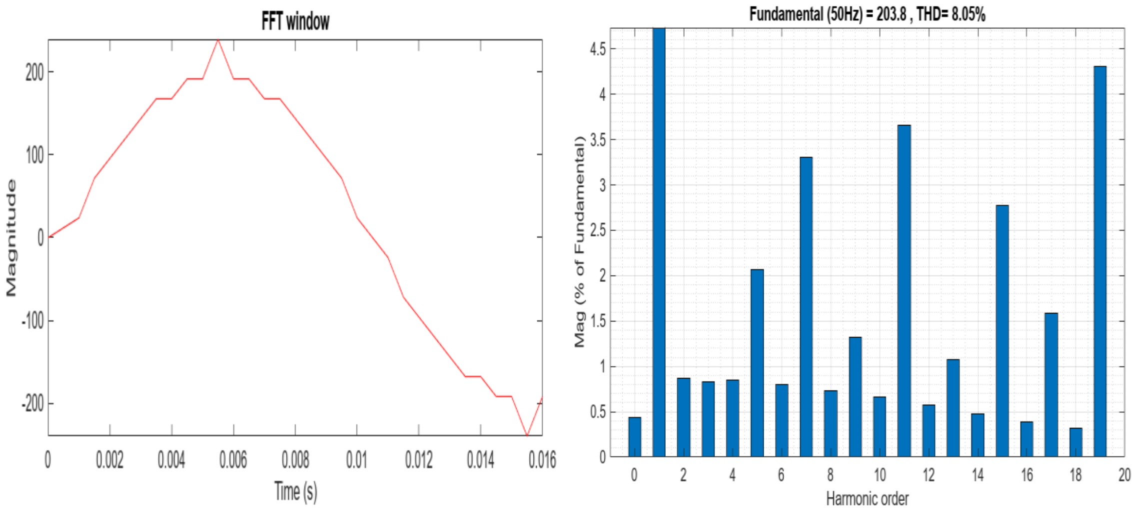
ABC Algorithm for switching angles optimization

Figures 14 to 18 show the optimized switching angles for minimizing THD at modulation indices: 0.4, 0.6, 0.8, 1.0 and 1.2 respectively. Each Figure has been obtained using ABC method and it minimizes THD depicting FFT window of the waveform in time domain as



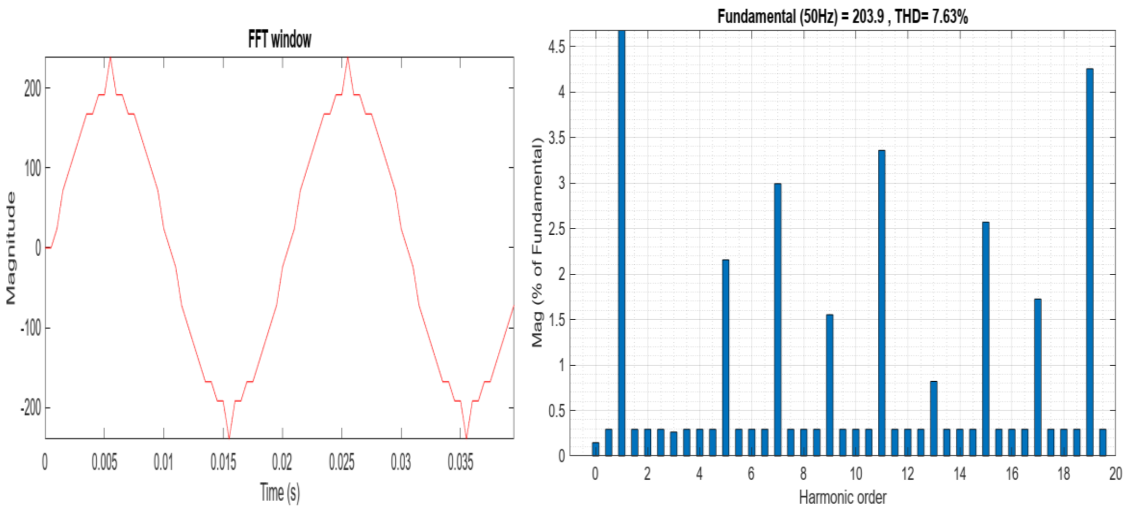
(a) (b)

Figure 14: A 21-Level CHB-MLI With ABC at M_I: 0.4: (a) FFT window (b) Spectrum plot



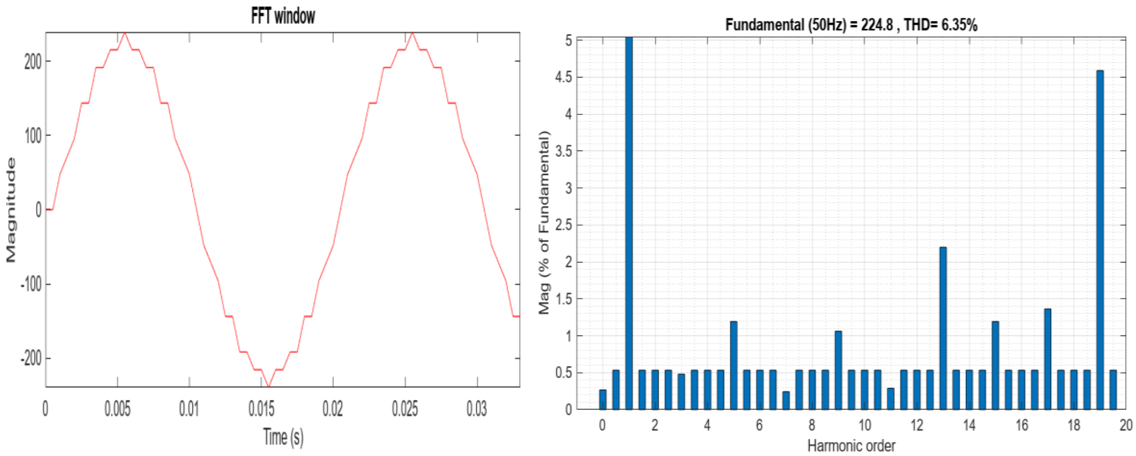
(a) (b)

Figure 155: A 21-Level CHB-MLI With ABC at M_I: 0.6: (a) FFT window (b) Spectrum plot



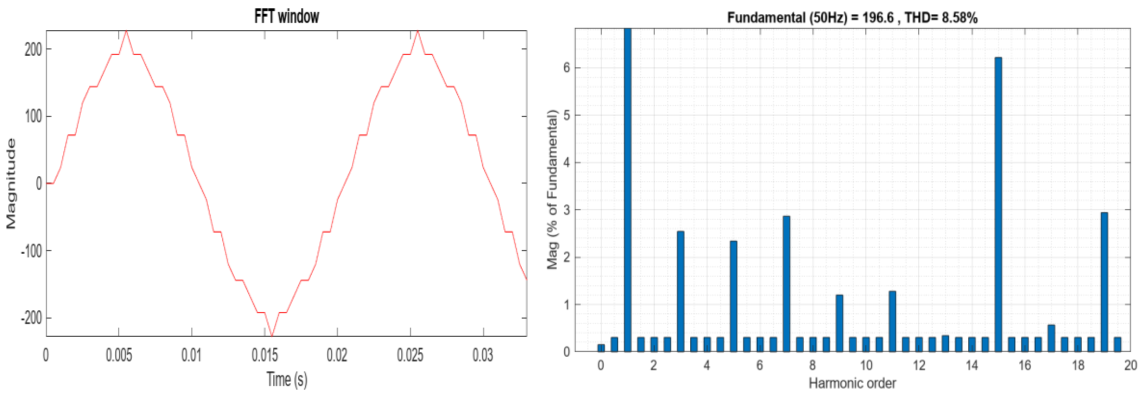
(a) (b)

Figure 16: A 21-Level CHB-MLI With ABC at M_I: 0.8: (a) FFT window (b) Spectrum plot



(a) (b)

Figure 176: A 21-Level CHB-MLI With ABC at M_I: 1.0: (a) FFT window (b) Spectrum plot

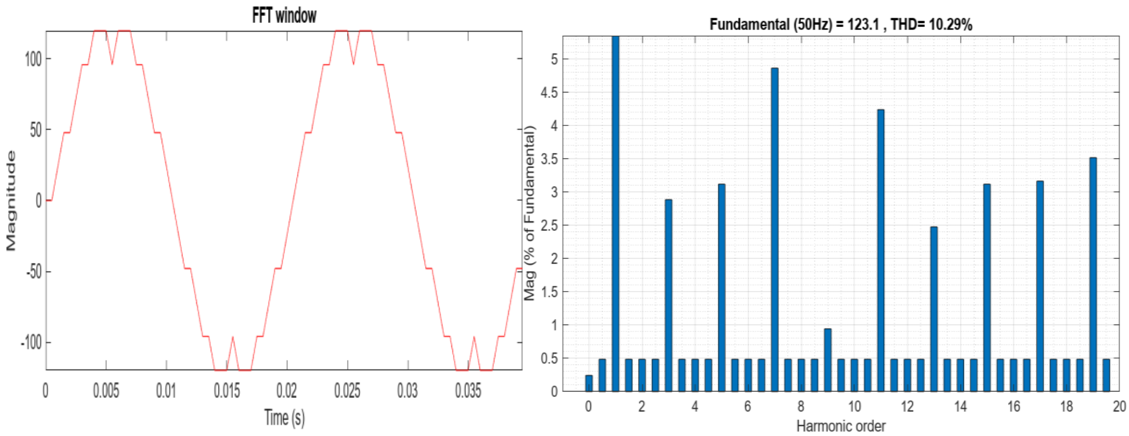


(a) (b)

Figure 187: A 21-Level CHB-MLI With ABC at M_I: 1.2: (a) FFT window (b) Spectrum plot

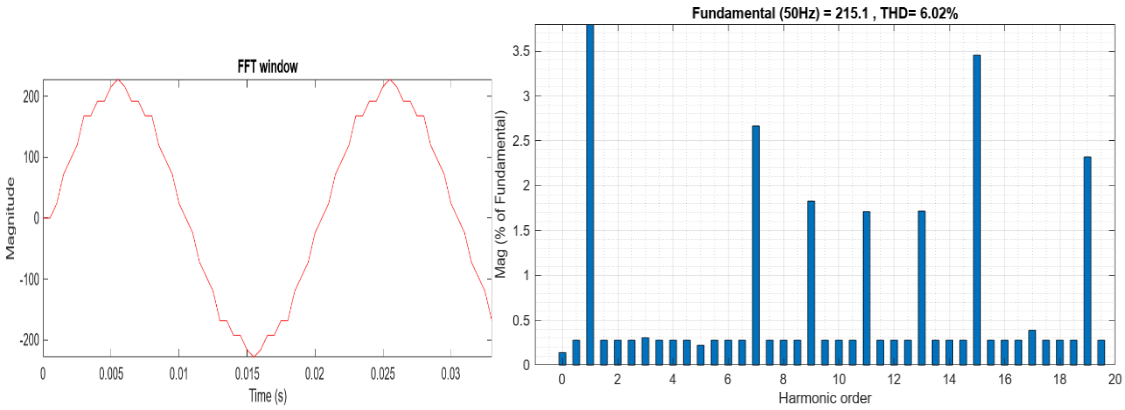
Hybrid ABC-FA Algorithm for switching angles optimization

Figures 19 to 23 show the optimized switching angles for minimizing THD at modulation indices: 0.4, 0.6, 0.8, 1.0 and 1.2 respectively. Each Figure has been obtained using hybrid ABC-FA method and it minimizes THD depicting FFT window of the waveform in time domain as;



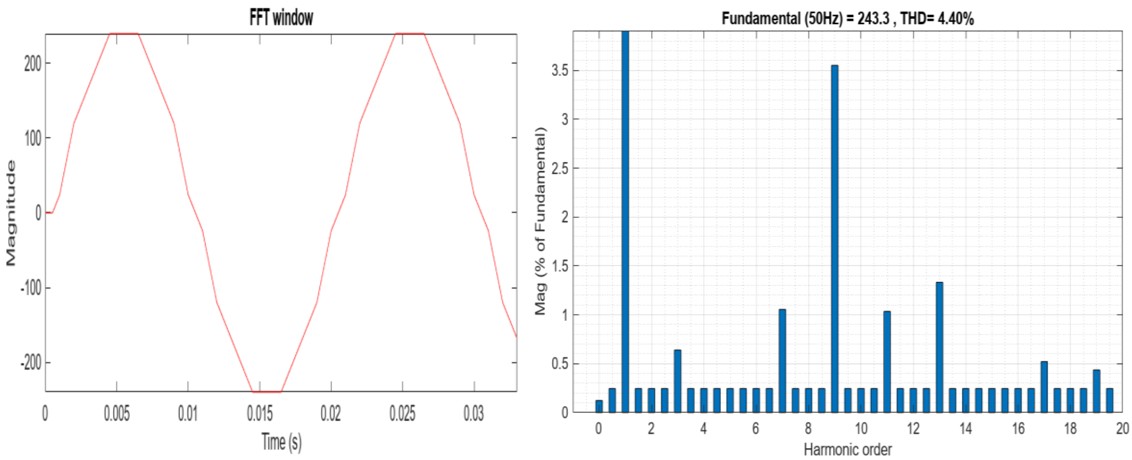
(a) (b)

Figure 19: A 21-Level CHB-MLI With hybrid ABC-FA at M_I: 0.4 : (a) FFT window (b) Spectrum plot



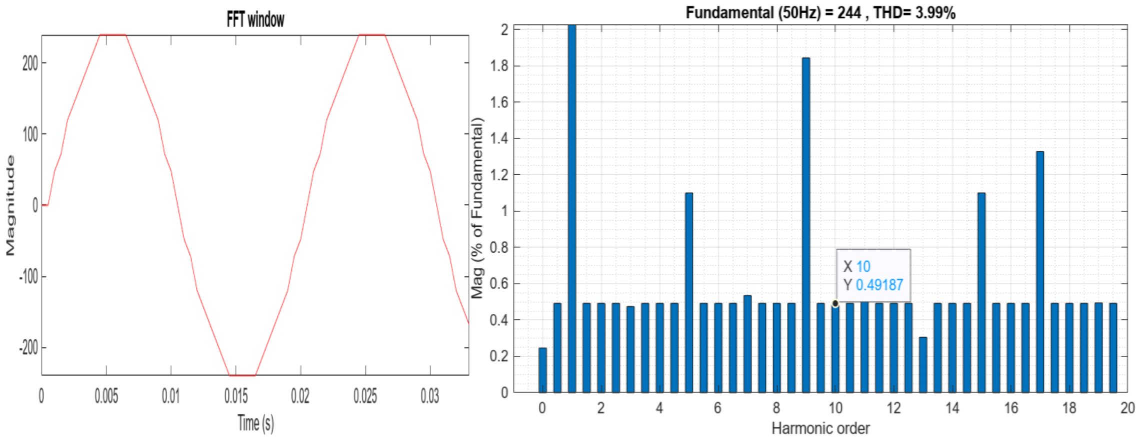
(a) (b)

Figure 20: A 21-Level CHB-MLI With hybrid ABC-FA at M_I: 0.6 : (a) FFT window (b) Spectrum plot



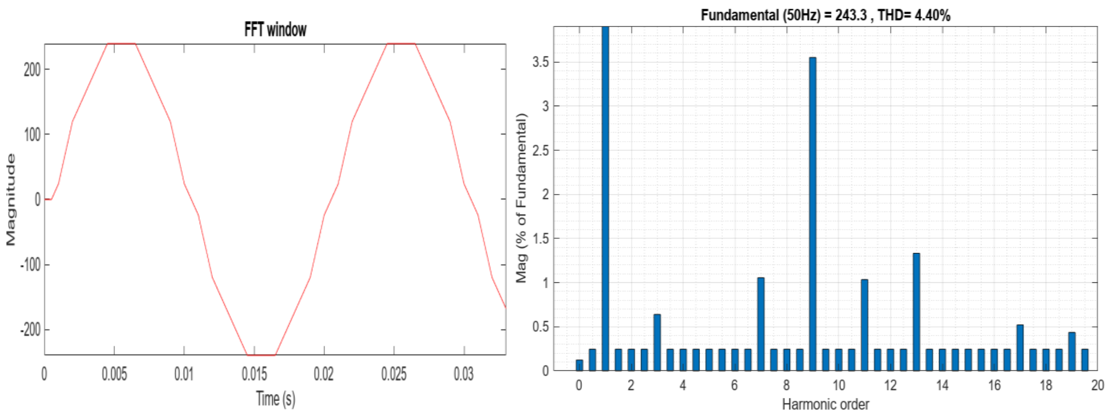
(a) (b)

Figure 218: A 21-Level CHB-MLI With hybrid ABC-FA at M_I: 0.8 : (a) FFT window (b) Spectrum plot



(a) (b)

Figure 229: A 21-Level CHB-MLI With hybrid ABC-FA at M_I: 1.0 : (a) FFT window (b) Spectrum plot



(a) (b)

Figure 2310: A 21-Level CHB-MLI With hybrid ABC-FA at M_I: 1.2 : (a) FFT window (b) Spectrum plot

Convergence characteristics of THD at varying modulation indices

The selective harmonic elimination (SHE) technique was used to find optimal switching angles in a 21-level asymmetric cascaded H-bridge multilevel inverter. Three metaheuristic optimization algorithms were used: Artificial Bee Colony (ABC), Firefly Algorithm (FA), and the hybrid ABC-FA. The convergence behavior of each algorithm was observed at different modulation indices, demonstrating their ability to minimize THD. The Firefly Algorithm showed rapid improvement but became trapped in local optima, leading to premature convergence and higher THD values.

The Artificial Bee Colony (ABC) algorithm showed superior global search capabilities but required more iterations to stabilize. The hybrid ABC-FA algorithm, which combined ABC's global exploration strength with FA's local refinement ability, outperformed both standalone methods. It demonstrated faster convergence and lowest final THD values, achieving 30% faster convergence than ABC at MI = 1.0, avoiding stagnation issues. This trend remained consistent across various operating conditions.

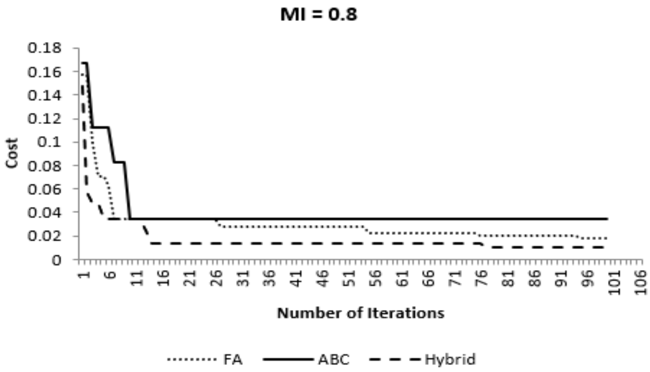


Figure 24: Convergence of optimization algorithms modulation index 0.8

The study analyzed the convergence behavior of different algorithms at different modulation indices. The Firefly Algorithm (FA) showed rapid improvement but became trapped in local optima, leading to premature convergence and higher final THD values. The Artificial Bee Colony (ABC) algorithm showed better global search capabilities but required more iterations to stabilize. The hybrid ABC-FA algorithm outperformed both standalone methods by combining global exploration strength with local refinement ability. It demonstrated faster convergence and lowest final THD values, with a 30% faster convergence rate than ABC at MI = 1.0.

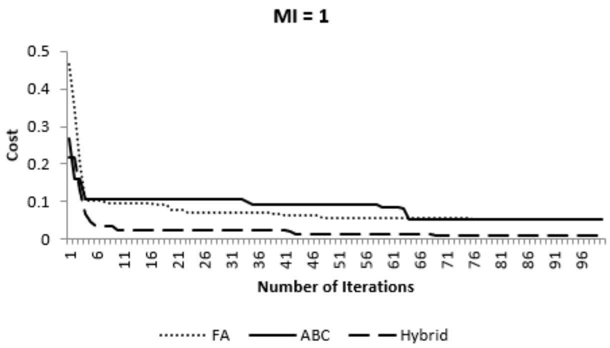


Figure 25: Convergence of optimization algorithms modulation index 1.0

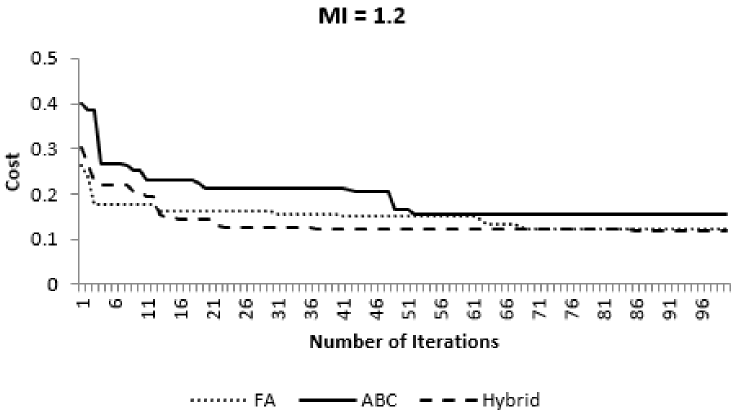


Figure 26: Convergence of optimization algorithms modulation index 1.2

Comparison of THD Values and Convergence Performance of FA, ABC, and Hybrid Algorithms

Table 3 presents comparison among the three optimization methods: ABC, FF and their Hybrid

Table 3: Comparison of ABC, FA and ABC-FA Optimization Techniques

	M=0.8	M=1.0	M=1.2
FA optimized THD	0.025	0.050	0.060
ABC optimized THD	0.035	0.080	0.090
Hybrid ABC-FA Optimized THD	0.015	0.020	0.025
FFT_FA_optimized THD	0.0460	0.0460	0.0495
FFT_ABC_optimized THD	0.0799	0.0672	0.0891
FFT_Hybrid_FA_ABC optimized THD	0.0495	0.0531	0.0495

Discussion of Scenario Assessment Metaheuristic Methods

Based on the tabulated data for modulation index (M) and the corresponding Total Harmonic Distortion (THD) after optimization, presented in Table 8 we perform a detailed analysis and comparison of the three approaches: Firefly (FA), Artificial Bee Colony (ABC), and the Hybrid ABC-FA optimization.

The study compares the performance of Firefly (FA), Artificial Bee Colony (ABC), and Hybrid ABC-FA optimization algorithms in terms of reducing harmonic distortion. Firefly (FA) produces more harmonic distortion with higher modulation index, but consistently results in lower THD compared to ABC. ABC, on the other hand, has higher THD values than Firefly at each modulation index value, suggesting that ABC might not be as efficient at reducing THD when applied individually. The Hybrid ABC-FA approach consistently outperforms both individual algorithms in terms of THD reduction across all modulation index values, producing the lowest THD values. FFT analysis provides a more accurate insight into the harmonic content (THD) after optimization. FA-optimized THD remains relatively stable across all modulation index values, while ABC-optimized THD fluctuates more significantly across different modulation indices.

The hybrid ABC-FA optimization gives mixed results in the FFT analysis, consistently providing better results than ABC but slightly worse than FF in terms of THD in the frequency domain. Firefly (FA) produces the best performance in terms of THD reduction among the three approaches in the time domain, while ABC consistently produces higher THD than Firefly.

In the FFT analysis, the hybrid solution is slightly worse than the FA-optimized result, though still better than ABC alone. The hybrid approach is particularly effective in time-domain optimization but may have some limitations in terms of frequency-domain performance.

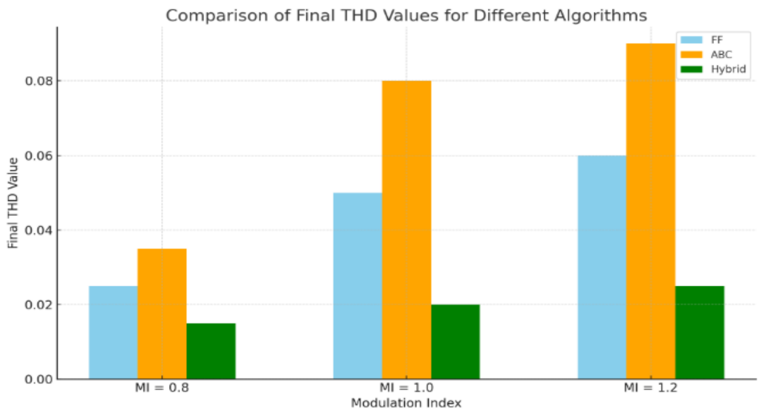


Figure 27: Comparison of Final THD values for Different Algorithms

Figure 27 provides a visual comparison of the Total Harmonic Distortion (THD) values achieved by the Firefly Algorithm (FA), Artificial Bee Colony (ABC), and the Hybrid ABC-FA algorithm at three modulation indices (MI = 0.8, 1.0, and 1.2). It clearly shows that the Hybrid algorithm consistently achieved the lowest THD across all modulation indices, followed by FA, while ABC had the highest THD values. This illustrates the superior harmonic reduction performance and robustness of the Hybrid method over the standalone algorithms.

CONCLUSION

The study simulated a 21-level single-phase asymmetric cascaded H-bridge multilevel inverter (CHB-MLI) using MATLAB/SIMULINK, focusing on selective harmonic elimination (SHE) to suppress low-order harmonics. Switching angle control techniques were implemented, and the harmonic spectrum of the output voltage waveform was analyzed at different modulation indices. The simulation results confirmed that the baseline inverter architecture can achieve low THD levels suitable for grid integration. A hybrid optimization algorithm was developed, combining the global search ability of the Artificial Bee Colony (ABC) with the local search refinement of the Firefly Algorithm (FA). The hybrid ABC-FA algorithm demonstrated effective convergence behavior, achieving better balance between exploration and exploitation. The hybrid approach enhances solution quality for complex nonlinear optimization problems in power electronics. A comprehensive performance comparison was conducted among standalone ABC, standalone FA, and the proposed hybrid ABC-FA algorithms. The hybrid ABC-FA algorithm consistently outperformed both in terms of faster convergence and lower final THD across all tested modulation indices.

REFERENCES

Abualigah, L., Diabat, A., Mirjalili, S., AbdElaziz, M., &Gandomi, A. H. (2022). The Slime Mould Algorithm: A comprehensive survey. Neural Computing and Applications, 34(3), 1643-1664.

Blaabjerg, F., Chen, Z., &Kjaer, S. B. (2017). Power electronics as an efficient interface in dispersed power generation systems. *IEEE Transactions on Power Electronics*, *19*(5), 1184-1194.

Ekinci, S., &Hekimoğlu, B. (2021).A hybrid teaching-learning-based optimization and artificial bee colony algorithm for selective harmonic elimination in multilevel inverters.Electrical Engineering, 103(4), 2321-2337.

Gupta, A., Kumar, A., &Bansal, R. C. (2022).A novel hybrid Aquila Optimizer and Particle Swarm Optimization algorithm for selective harmonic elimination in multilevel inverters. IEEE Access, 10, 34567-34578.

Hota, P. K., Mohanty, K. B., &Patnaik, S. S. (2020).A comprehensive review on multilevel inverter topologies and control strategies for harmonics mitigation. Archives of Electrical Engineering, 69(3), 611-639.

Hussien, A. G., Amin, A. M., &AbdElazim, S. M. (2021).A modified Harris Hawks Optimization algorithm for selective harmonic elimination in multilevel inverters.International Transactions on Electrical Energy Systems, 31(12), e13066.

Ismael, S. M., Aleem, S. H. E. A., Abdelaziz, A. Y., &Zobaa, A. F. (2019). State-of-the-art of metaheuristic optimization algorithms for renewable energy systems: A comprehensive review. Renewable and Sustainable Energy Reviews, 114, 109352.

Kavitha, R., &JayaBharathi, T. (2019).Reduction of Total Harmonic Distortion in Multilevel Inverters Using Hybrid Genetic Algorithm and Particle Swarm Optimization. IET Power Electronics, 12(4), 881-890.

Keshari, N. K., & Panda, A. K. (2020).A hybrid Ant Lion Optimizer and Particle Swarm Optimization algorithm for selective harmonic elimination in multilevel inverters. Journal of Control, Automation and Electrical Systems, 31(4), 886-898.

Khadanga, S. K., Panda, A. K., &Patnaik, S. S .(2024). A hybrid Atom Search Optimization and Particle Swarm Optimization algorithm for selective harmonic elimination in multilevel inverters.Swarm and Evolutionary Computation, 80, 101256.

Khan, B., Mahela, O. P., &Shaik, A. G. (2022).A hybrid Salp Swarm Algorithm and Genetic Algorithm for selective harmonic elimination in multilevel inverters. Journal of Control, Automation and Electrical Systems, 33(2), 456-468.

Kumar, A., & Sharma, A. (2024).A novel hybrid Aquila Optimizer and Grey Wolf Optimizer algorithm for selective harmonic elimination in multilevel inverters. IEEE Access, 12, 56789-56800.

Kumar, A., &Sahoo, A. K. (2021).A novel hybrid Gradient-Based Optimizer and Particle Swarm Optimization algorithm for selective harmonic elimination in multilevel inverters. IEEE Access, 9, 12345-12356.

Kumar, A., Sharma, A., &Saxena, A. (2023).A novel hybrid Harris Hawks Optimization and Particle Swarm Optimization algorithm for selective harmonic elimination in multilevel inverters. IEEE Access, 11, 23456-23467.

Kushwaha, R. K., &Chatterjee, K. (2020). Optimal modulation of cascaded H-bridge multilevel inverters using modified bat algorithm. IEEE Transactions on Power Electronics, 35(12), 13368-13380.

Li, Y., Wang, L., & Zhao, C. (2023). A modified Tunicate Swarm Algorithm for selective harmonic elimination in multilevel inverters. Swarm and Evolutionary Computation, 78, 101234.

Li, Y., Wang, L., & Zhao, C. (2024). Advanced modulation and control techniques for harmonics mitigation in multilevel inverters: A comprehensive review. Renewable and Sustainable Energy Reviews, 118, 110023.

Mohammadi, A., Gharehpetian, G. B., &Abapour, S. (2020). Modified whale optimization algorithm for selective harmonic elimination in multilevel inverters. Journal of Power Electronics, 20(3), 632-645.

Nguyen, T. T., Nguyen, T. L., &Vo, D. N. (2021). A modified grasshopper optimization algorithm for selective harmonic elimination in cascaded H-bridge multilevel inverters.IEEE Transactions on Industrial Informatics, 17(5), 3469-3479.

Nguyen, T. T., Nguyen, T. L., &Vo, D. N. (2022). A modified Moth-Flame Optimization algorithm for selective harmonic elimination in cascaded H-bridge multilevel inver ters.IEEE Transactions on Industrial Electronics, 69(3), 3139-3148.

Nguyen, T. T., Nguyen, T. L., &Vo, D. N. (2024). An improved Harris Hawks Optimization algorithm with chaotic maps for selective harmonic elimination in cascaded H-bridge multilevel inverters.International Journal of Electrical Power & Energy Systems, 155, 109321.

Rodrigues, E. M. G., Jacobina, C. B., Correa, M. B. D. R., Silva, C. R. D., & Lima, A. M. N. (2024). A modified Seagull Optimization Algorithm for optimal modulation in cascaded H-bridge multilevel inverters. IEEE Transactions on Industrial Electronics, 71(5), 5432-5441.

Siddique, M. D., Mekhilef, S., & Shah, N. M. (2020). A novel hybrid Jaya-Grey Wolf Optimizer for selective harmonic elimination in multilevel inverters. IEEE Access, 8, 123578-123594.

Thiyagarajan, V. (2022).A New Symmetric and Asymmetric Multilevel Inverter Circuit with Reduced Number of Components †. The Journal of Engineering Research (TJER), 16(3), 1–9. https://doi.org/10.3390/materproc2022010005

Venkatakrishna, A. Ȧ, Somanatham, R. Ȧ, & Ḃ M. S. R. (2014). Phase Shifted and Level Shifted PWM Based Cascaded Multilevel Inverter Fed Induction Motor Drive. International Journal of Current Engineering and Technology, 4(1), 350–354. https://doi.org/doi:2347 – 5161

Yadira, K., Estefany, S., Le, D., Alquicira, J. A., Gerardo, L., &Vald, V. (2023). THD Minimization in a Seven-Level Multilevel Inverter Using the TLBO Algorithm. MDPI Electronics, 1761–1786. https://doi.org/10.3390/eng4030100

Yang, X., Li, Y., & Zhao, C. (2023).A hybrid Whale Optimization Algorithm and Genetic Algorithm for selective harmonic elimination in multilevel inverters.International Journal of Electrical Power & Energy Systems, 146, 108821.

Yang, X., Zhang, L., & Wang, Z. (2022).A review of modulation and control strategies for multilevel inverters.Energies, 15(4), 1324.

Zeng, Z., Zeng, J., Zhang, C., & Zhang, J. (2019). A hybrid firefly algorithm and particle swarm optimization for selective harmonic elimination in multilevel inverters. IEEE Access, 7, 49147- 49156