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Voltage Total Harmonic Distortion Reduction in Multi-level Single-Phase Inverters using the SHE-PWM Technique with a TLBO Algorithm

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Abstract: This paper presents a modulation method based on the selective harmonic elimination-pulse width modulation (SHE-PWM) technique. The aim is to determine the optimal switching angles (SA) using the teaching learning-based optimization algorithm (TLBOA), capable of reducing the voltage total harmonic distortion (THD) present in the output waveform of single-phase multi-level inverters (MLIs). The performance of proposed technique has been verified through simulation using Matlab script and Simulink environment. The TLBOA-based SHE-PWM technique is applied to a 17-level inverter to eliminate 5^{th}, 7^{th}, 11^{th}, 13^{th}, 17^{th}, 19^{th} and 23^{rd} harmonics, achieving an improvement of up to 4.31% in the phase voltage THD content in the range of modulation index (MI) 0.5 to 0.95. Furthermore, the superiority of the proposed technique was confirmed by comparison with conventional modulation techniques, which showed that the proposed technique produces lower THD than those used in the equal phase (EP), half-equal phase (HEP), feed forward (FF) and half height (HH) methods.

Keywords: SHE-PWM technique, TLBO algorithm, total harmonic distortion, conventional modulation techniques

Introduction

In recent years, multi-level inverters (MLIs) have been extensively employed in renewable energy applications and diverse industrial sectors, providing numerous benefits compared to traditional two-level inverters (TLIs). They have received an increasing interest from people in research and academia. In the research literature, there are three basic MLIs configuration: Diode-Clamped MLI (DC-MLI) (Adam et al., 2012), Flying Clamped MLI (CC-MLI) (Meynard et al., 1992) and Cascaded H-Bridge MLI (CHB-MLI) (Chunyan et al., 2015). Compared to TLIs, MLIs have many advantages including, lower electromagnetic interference (EMI), minimizing (dv/dt) across switches and suitability for medium or high voltage high power applications such as wind turbines (WT), photovoltaic systems (PVS) and electric vehicles (EV) (Charan et al., 2015; Sedaghati et al., 2023; Elias et al., 2022; Taiea et al., 2019; Pires et al., 2017; Sotoodeh et al., 2013; Mehta et al., 2022; Meraj et al., 2023).

To enhance the efficiency and performance of MLIs, numerous modulation techniques, new topologies and optimal operating strategies have been reported in the literature (Behera et al., 2022), (Kubendran et al., 2022; Singh et al., 2022; Kannan et al., 2022). Pulse width modulation (PWM) techniques are the most popular

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techniques employed for controlling the MLI (Juárez-Abad et al., 2021). Different PWM techniques have been developed, such as the sinusoidal PWM (S-PWM) technique and space vector PWM (SV-PWM) technique (Can et al., 2022; Dordevic et al., 2013). Nevertheless, both S-PWM and SV-PWM techniques (Ren et al., 2021) operate with high switching frequencies, resulting in increases the switching losses. The switching losses can be reduced by using a selective harmonic elimination -pulse width modulation (SHE-PWM) technique (Hiendro et al., 2020; Dahidah et al., 2008). Compared with S-PWM and SV-PWM techniques, SHE-PWM is a more effective MLIs control technique to achieve better harmonic performance even at low switching frequencies. The main advantage of SHE-PWM technique is the adaptation of suitable switching angles in multilevel inverters to get rid of or lower some low-order selective harmonics while maintaining the fundamental harmonic at a desired value. However, the main challenge in SHE-PWM technique is to find the set of solutions of non-linear equations that define the optimal switching angles (M. Bounabi et al., 2018). In the research literature, the techniques used to address this problem can be classified into three categories, algebraic methods (e.g., Walsh method (Vicente et al., 2011), Groebner Bases (Yang et al., 2015), etc.), numerical methods (e.g., homotopy algorithm (Hosseini Aghdam et al., 2013), Newton Raphson method (Kato et al., 1999), etc.) and metaheuristics-based algorithms (e.g., genetic algorithm (Ali et al., 2021), particle swarm optimization (PSO) (Jiang et al., 2022), etc.) as summarized in Figure. 1.

In this work, a selective harmonic elimination PWM (SHE-PWM) technique using a teaching learning based optimization (TLBO) algorithm is proposed to obtain optimal switching angles to minimize the output voltage total harmonic distortion (THD) of a 17-level single-phase cascaded H-bridge multi-level inverter (CHB-MLI). The main objective is to demonstrate the effectiveness of the (TLBO) algorithm in addressing selective harmonic elimination (SHE) and total harmonic distortion (THD) minimization in multi-level inverters (MLIs) by optimally determining the switching angles. The main contributions of the present work can be summarized as follows:

- An effective teaching learning based optimization (TLBO) meta-heuristic algorithm is adopted to solve the non-linear (SHE-PWM) problem.
- The TLBO algorithm is implemented to find the optimal switching angles that effectively reduce the THD and meet the IEEE 519-2014 standard.
- The proposed technique is applied on 17-level (CHB) inverters for varying modulation index values.
- Comparison of the performance of the proposed method with conventional modulation methods (EP, HEP, FF and HH methods) is carried out to assess its superiority.

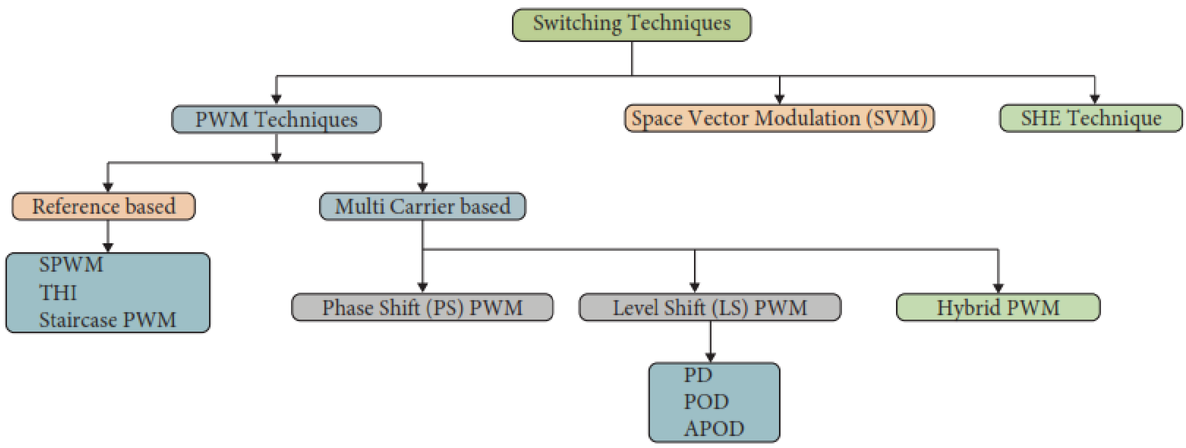

Figure 1. Classification of switching techniques (Dekka et al., 2020)

Methodology

This section outlines the application of the Teaching Learning based Optimization (TLBO) algorithm to solve the selective harmonic elimination-pulse width modulation (SHE-PWM) problem. More precisely, the solution of a set of non-linear equations and finding the optimal switching angles for eliminating the selected lower order harmonics and reducing the total harmonic distortion (THD) from the cascaded H-bridge multilevel inverter (CHB-MLI) output. The simulations of single-phase 17-level CHB inverter will be done according to the switching angles obtained from the TLBO algorithm. Additionally, the THD values were compared with those reported in the available literature obtained using different conventional modulation techniques.

Single-Phase Eleven-Level CHB-MLI

In this section, Selective Harmonic Elimination (SHE) strategy is used to produce the switching pulses using optimal switching angles for a single-phase cascaded H-bridge multilevel inverter (CHB-MLI) having the ability to produce a 17-level output voltage. Figure. 2 shows the structural design for single-phase 17-level CHB-MLI. This structure consists of 8 individual H-bridge cells connected with each other in a cascaded configuration. Each of these H-bridge cells has 4 switches and 1 DC supply, making a total of 32 switches and 8 DC supplies. All the DC supplies are equal in magnitude, making it a symmetrical configuration. The combination of all the H-bridge cells is generating the 17-level desired output voltage. Figure. 3 illustrates the staircase output voltage of the 17- level CHB- MLI for the quarter waveform of voltage cycle. Through the Figure, it can be seen that each edge of each stair represents one switching angle. These switching angles are considered as keys to eliminate selective harmonics. The switching angle θ_1 is used to control the fundamental component of the output voltage while all remaining switching angles (θ_2 to θ_8) are used to remove the harmonics. Generally, this SHE strategy is conducted by decoding the pulse width modulation (PWM) waveform utilizing Fourier analysis. Fourier series of periodic functions can be expressed as follows:

$$f(t) = \frac{A_0}{2} + \sum_{n=1}^{\infty}\left[A_n \cos(n\omega t) + V_n \sin(n\omega t)\right] \tag{1}$$

In this case $f\left(t\right) = odd$, so equation (1) can be rewritten as follows:

$$f(t) = \sum_{n=1}^{\infty} V_n \sin\left(n\omega t\right) \tag{2}$$

Here, the voltage component V_n can be determined via the following equation:

$$V_n = \frac{4V_{dc}}{n\pi}\sum_{i=1}^{i}\cos(n\theta_i) \tag{3}$$

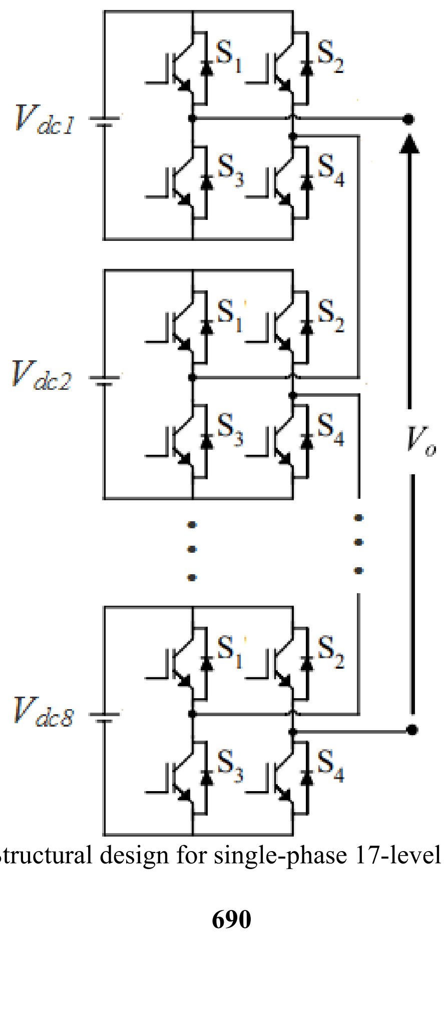

Figure 2. Structural design for single-phase 17-level (CHB-MLI)

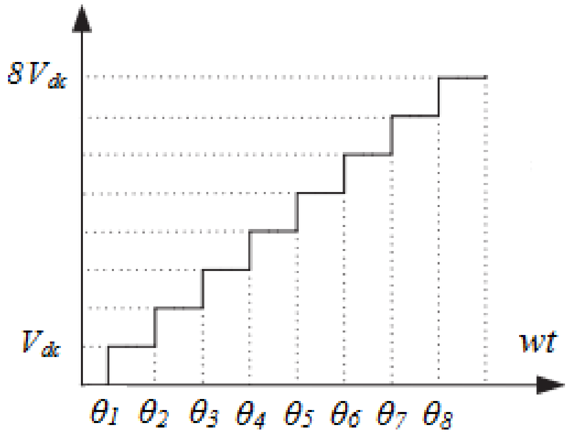

Figure 3. Quarter waveform of a 17-level inverter

Equation (4) provides the formula for the (SHE) equations for the 17-level inverter. A non-linear set of equations is used to eliminate the specific harmonics (5th, 7th, 11th, 13th, 17th, 19th, and 23th) from the output voltage. This non-linear equation set is achieved from (4) by equating V_5, V_7, V_{11}, V_{13}, V_{17}, V_{19}, and V_{23} to zero as follows:

$$
\begin{aligned}
V_1 &= \frac{4V_{dc}}{\pi}\left[\cos(\theta_1)+\cos(\theta_2)+\ldots+\cos(\theta_8)\right]=M\\
V_5 &= \frac{4V_{dc}}{5\pi}\left[\cos(5\theta_1)+\cos(5\theta_2)+\ldots+\cos(5\theta_8)\right]=0\\
V_7 &= \frac{4V_{dc}}{7\pi}\left[\cos(7\theta_1)+\cos(7\theta_2)+\ldots+\cos(7\theta_8)\right]=0\\
V_{11} &= \frac{4V_{dc}}{11\pi}\left[\cos(11\theta_1)+\cos(11\theta_2)+\ldots+\cos(11\theta_8)\right]=0\\
V_{13} &= \frac{4V_{dc}}{13\pi}\left[\cos(13\theta_1)+\cos(13\theta_2)+\ldots+\cos(13\theta_8)\right]=0\\
V_{17} &= \frac{4V_{dc}}{17\pi}\left[\cos(17\theta_1)+\cos(17\theta_2)+\ldots+\cos(17\theta_8)\right]=0\\
V_{19} &= \frac{4V_{dc}}{19\pi}\left[\cos(19\theta_1)+\cos(19\theta_2)+\ldots+\cos(19\theta_8)\right]=0\\
V_{23} &= \frac{4V_{dc}}{23\pi}\left[\cos(23\theta_1)+\cos(23\theta_2)+\ldots+\cos(23\theta_8)\right]=0
\end{aligned} \tag{4}
$$

According to the (SHE) strategy. With N switching angles in a quarter-cycle, there are N−1 harmonic components that can be eliminated. To eliminate 5th, 7th, 11th, 13th, 17th, 19th, and 23th order harmonics from the output voltage waveform. The equation (4) must be solved in such a way that the condition of ($0 < \theta_1 < \theta_2 < \ldots < \theta_8 < 90°$) is satisfied, where θ_1 to θ_8 represent switching angles. The optimum switching angles are calculated by utilizing an objective function. The TLBO algorithm finds the optimal solution using an objective function. This objective function is formulated as follows.

$$
\begin{aligned}
F(\theta_1,\theta_2,\theta_3,\ldots,\theta_8) &= \left(\sum_{i=1}^{8}\cos\theta_i - M\right)+\left(\frac{4}{5\pi}\sum_{i=1}^{8}\cos(5\theta_i)\right)+\left(\frac{4}{7\pi}\sum_{i=1}^{8}\cos(7\theta_i)\right)+\left(\frac{4}{11\pi}\sum_{i=1}^{8}\cos(11\theta_i)\right)\\
&+\left(\frac{4}{13\pi}\sum_{i=1}^{8}\cos(13\theta_i)\right)+\left(\frac{4}{17\pi}\sum_{i=1}^{8}\cos(17\theta_i)\right)+\left(\frac{4}{19\pi}\sum_{i=1}^{8}\cos(19\theta_i)\right)+\left(\frac{4}{23\pi}\sum_{i=1}^{8}\cos(23\theta_i)\right)
\end{aligned} \tag{5}
$$

The ratio of the THD% is a measure of the harmonic content of an output voltage or output current. THD% of the output voltage can be expressed as the following:

$$THD\% = 100 * \sqrt{\sum_{n=5,7,11,13,....}^{\infty} \left(\frac{V_n}{V_1}\right)^2} \tag{6}$$

Overview of the Teaching Learning Based Optimization (TLBO) algorithm

This optimization technique is an inhabited meta-heuristic technique that optimizes a given objective function (R. Venkata Rao et al., 2012). The TLBO algorithm exhibits two modes of learning: teacher-led learning and learner-led learning (referred to as the learner phase). The proposed TLBO algorithm considers the number of students in a class and the required number of iterations or generations. The teacher selects the best solution (learner), which is then reviewed by the other learners. The resulting solution is the most suitable one, requiring minimal data for implementation. The basic steps of the TLBO algorithm are given below:

Step 1: Initialize the parameters of TLBO algorithm: including the number of design parameters (D_n), the convergence rate and the sample size (P_n).
Step 2: Create a random population according to population size (n) and dimension.
Step 3: The optimization, during this phase, where the function f(x) that is to be minimized is defined subject to xi = 1, 2, ..., where i is the iteration size.

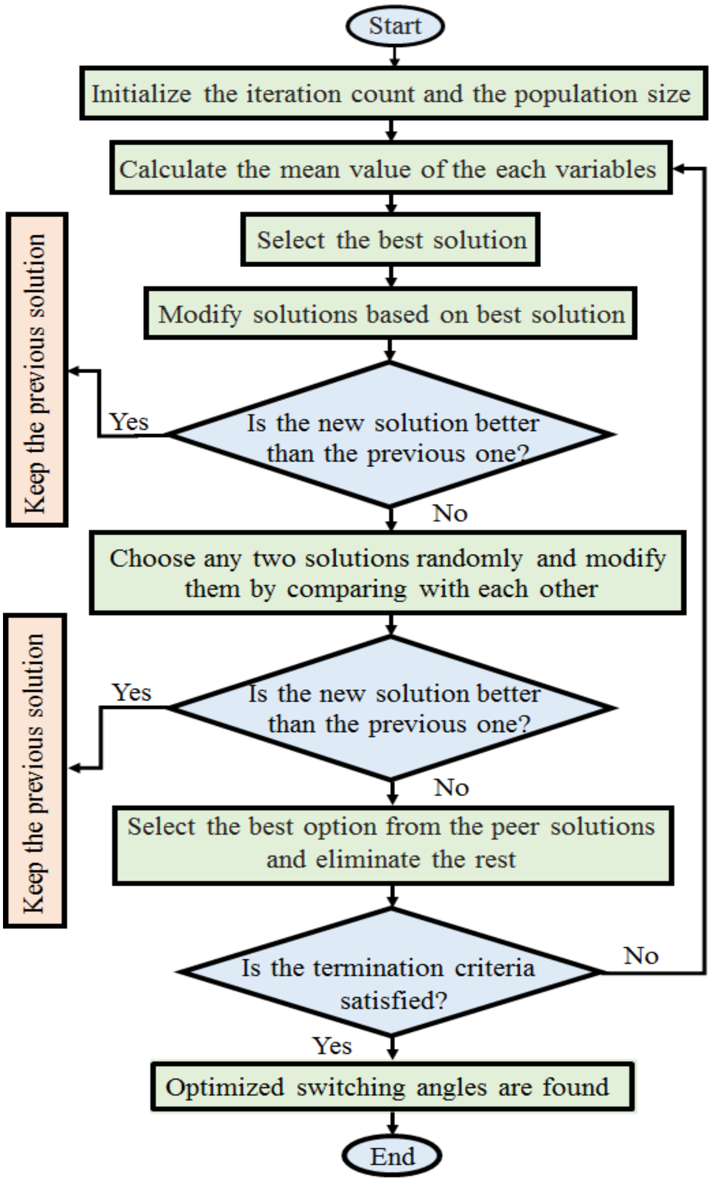

Figure 4. TLBO flowchart for solving SHE-PWM problem

Step 4: Find the mean of parameters by using an arbitrary population of the same size.
Step 5: The teacher phase, during this phase, the least fit student is the teacher, or the best solution X_{new} is employed, where X_{mean} is the mean of all the students in the class. The equation to generate a new solution is given by:

$$X_{new} = X + r.(X_{best} - T_f.X_{mean}) \tag{7}$$

where X_{best} represents the teacher, X_{new} represents the new selection, X represents the current solution, X_{mean} represents the mean of the solution, r represents a random number in the range (0, 1) and T_f represents the teaching factor and is either 1 or 2, the value of T_f is decided randomly.
Step 6: The learner phase, during this phase, learners gain information by interacting among themselves, the generate a new solution of this phase is expressed below:

$$X_{new} = X + r.(X - X_p) \tag{8}$$

where X_p is the partner solution, X represents the current solution and r represents a random number in the range (0, 1).
Step 7: Termination criteria. Termination criteria stop if the maximum generation is achieved; otherwise repeat from Step 5 and continue until all of the closure conditions are met. Detail flow chart of TLBO is shown in Figure 4.

Results and Discussion

In this section, a single-phase CHB-MLI to show the efficacy and robust of TLBO algorithm in solving SHE optimization problem. The inverter is a 17-level inverter, therefore 8 optimal angles are specified by the TLBO algorithm. The 17-level inverter with 315V output voltage and 50 Hz. The parameters of TLBO algorithm used for simulation are listed in Table (1).

Table 1. Simulation and optimization parameters

N^0	Parameters	Values
1	Population Size	100
2	Number of Iterations	500
3	Number of dimensions	10
4	Lower Boundary	[0°, 0°, 0°, 0°, 0°, 0°, 0°, 0°]
5	Upper Boundary	[90°, 90°, 90°, 90°, 90°, 90°, 90°, 90°]
6	Modulation index	$0 < MI \leq 1$

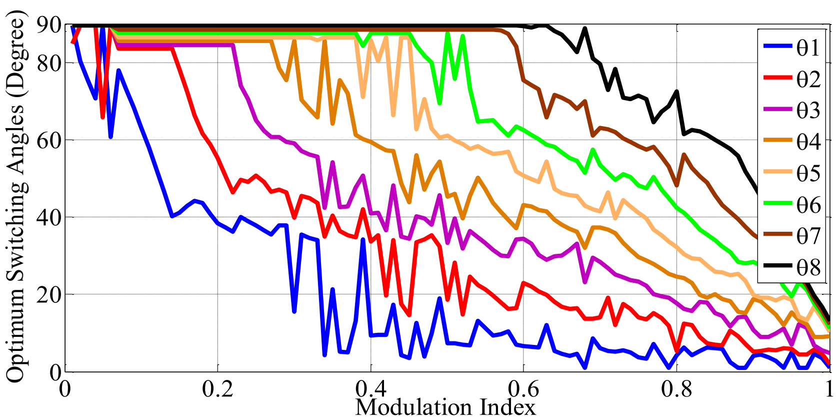

Figure 5. Optimum switching angle trend with modulation index obtained from TLBO algorithm

Figure. 5, shows optimal switching angles obtained using TLBO algorithm against different values of modulation index (MI). From the given Figure 5, it is evident that the value of the optimum solution set, comprising different switching angles (θ_1 to θ_8), converges to a lower value with the increase in the value of the (MI). The switching angles calculated by TLBO, THD% and fitness values versus different modulation indices for 17-level MLI are shown in Table 2.

Table 2. Simulation and optimization parameters

Switching Angle	MI 0.2	MI 0.6	MI 1
θ_1	38.38	6.67	1.90
θ_2	55.32	22.91	1.99
θ_3	84.55	34.33	4.86
θ_4	85.56	43.16	9.19
θ_5	87.54	50.67	10.99
θ_6	88.54	62.45	11.30
θ_7	89.50	75.35	12.40
θ_8	90	89.45	13.20

From Table 2, it is observed that the TLBO algorithm successfully solved the SHE equations in the range of 0.1–1 modulation index (MI) and interesting thing is that THD% produced during range 0.5–0.95 of MI are less than 8% and minimum THD% of value 4.31%. Figure. 6 shows the objective function value of TLBO algorithm versus modulation index. The Figure indicates that TLBO algorithms were successful in finding solutions across the entire modulation index range (0.1≤ MI ≤ 1). Moreover, TLBO algorithm produced the optimum fitness value of $6.75e^{-13}$, which demonstrates its stability and superior performance in solve the non-linear SHE-PWM problem

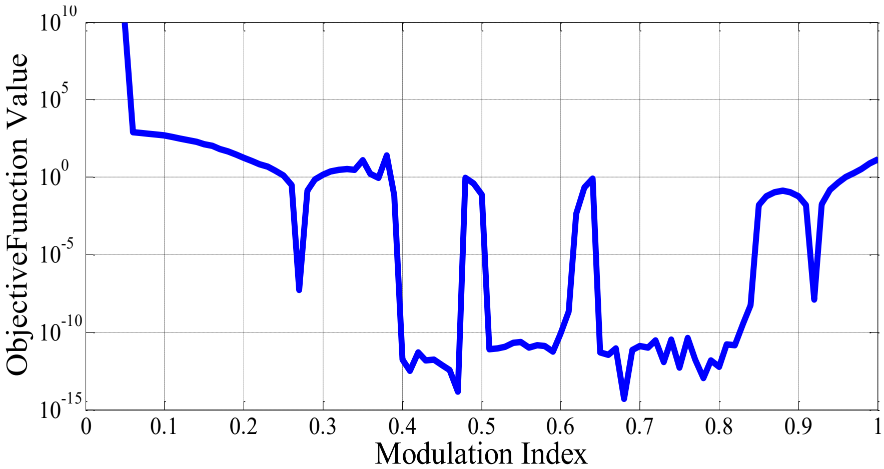

Figure 6. Objective function value for TLBO algorithm versus modulation index

Figure. 7 shows harmonics based on modulation index from 0.1 to 1. Figure. 7 indicates that the low order harmonics are eliminated 5th, 7th, 11th, 13th, 17th, 19th and 23th within the range of (0.5–0.95) modulation index. Figure. 8 represents the THD% of output voltage at various modulation index (MI).It can be seen that the THD% of output voltage value in the range of (0.5–0.95) modulation index, is found to be less than 8.0% and meets the IEEE 519-2014 standard and minimum THD% of value 4.31% has occurred.

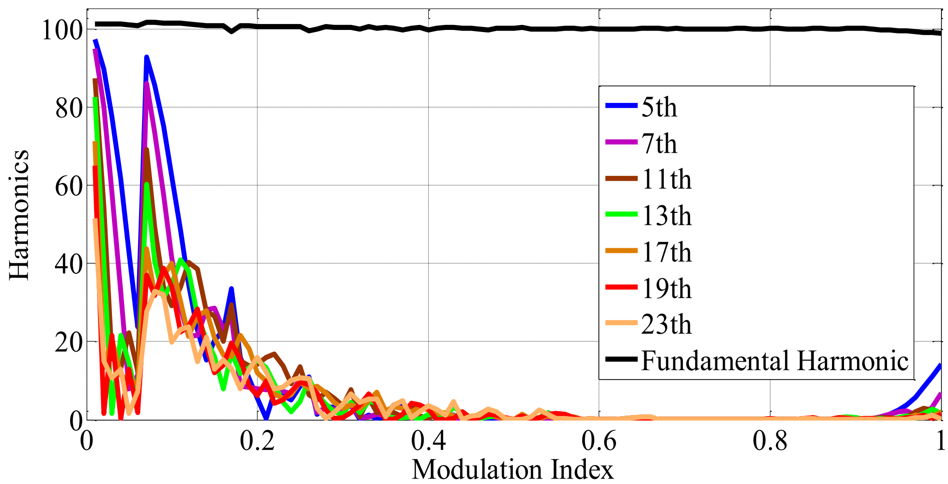

Figure 7. Harmonic trend with respect to the modulation index

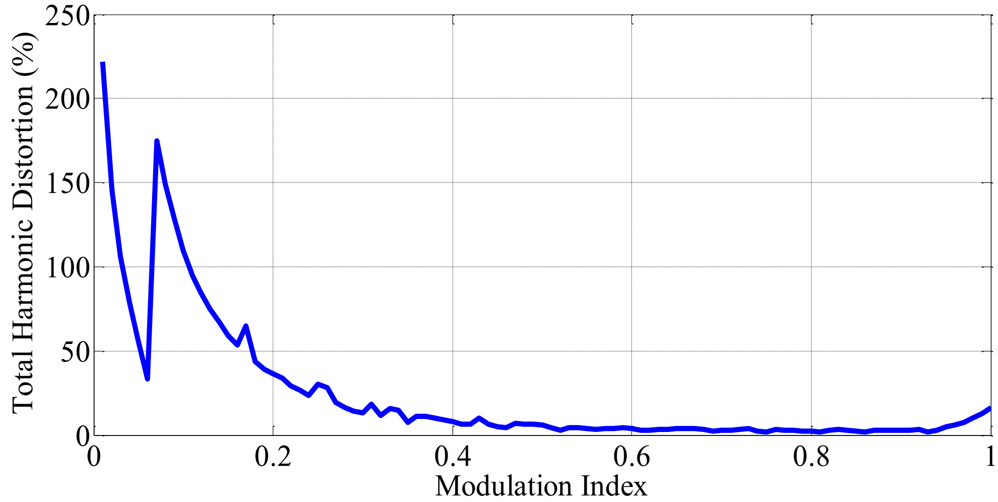

Figure 8. THD % Vs modulation index

Figure. 9 shows the magnitude of fundamental harmonic versus modulation index (MI). It can be observed the maximum deviation is within 1.3%. Figure. 10 depict the stepped output voltage waveform of 17-level a CHB-MLI with 0.8 modulation indexes using the TLBO. Fast Fourier transform (FFT) analysis at modulation index (MI) of value 0.8 is presented in Figure. 11. It reveals that the targeted lower order harmonics of 5^{th}, 7^{th}, 11^{th}, 13^{th}, 17^{th}, 19^{th} and 23^{th} are eliminated and the THD% is 4.31%, which complies with IEEE 519-2014 harmonic guidelines.

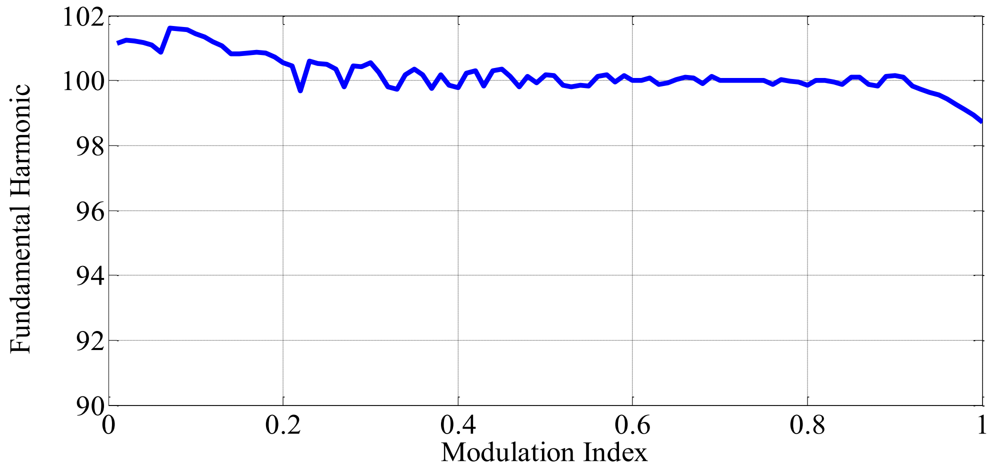

Figure 9. The calculated fundamental harmonic to V1

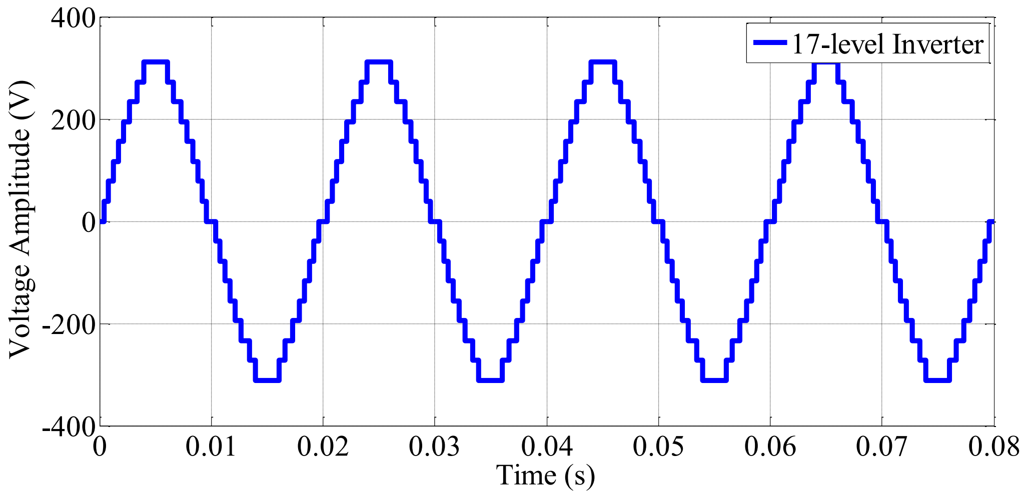

Figure 10. Simulation result of output voltage waveform for 17-level CHB-MLI at modulation index 0.8

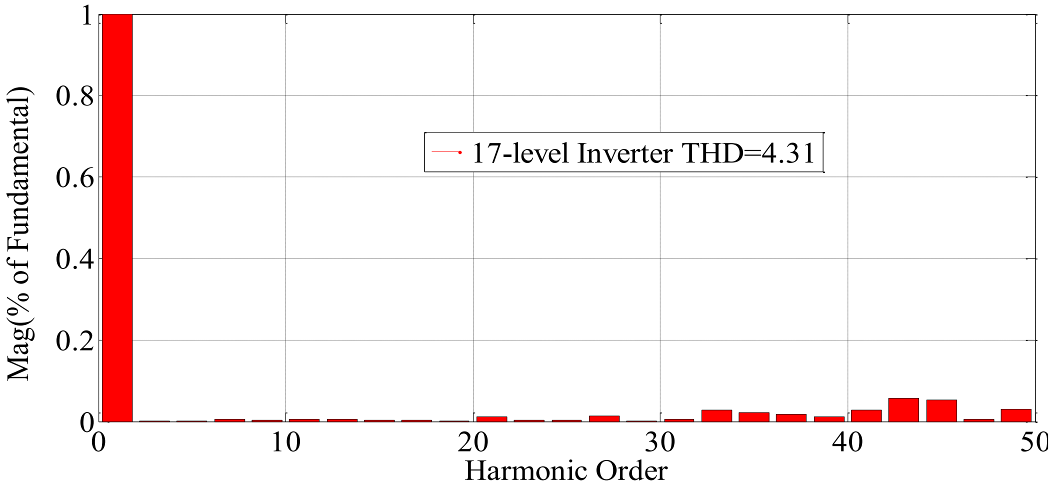

Figure 11. FFT analysis representing order of harmonics in the output voltage.

Table 3 summarizes the percentage of THD by EP, HEP, FF, HH and TLBO methods for voltage levels of 17. Noted that the best system performance is by TLBO method, in which the least THD obtained is 4.31%. This is because of better suppression of lower order harmonic spectrum by TLBO method.

Table 3. Comparative analysis of THD% at 17- level

Modulation technique	%THD
EP (Taha Abdulsalam Taha et al., 2025)	17.55%
HEP (Taha Abdulsalam Taha et al., 2025)	16.35%
FF (Taha Abdulsalam Taha et al., 2025)	20.90 %
HH (Taha Abdulsalam Taha et al., 2025)	5.02%
Proposed TLBO algorithm	4.31%

Conclusion

This paper focused on using the teaching learning-based optimization (TLBO) algorithm with selective harmonic elimination-pulse width modulation (SHE-PWM) technique to reduce total harmonic distortion (THD) on the phase voltage in a multilevel inverter (MLI) topology. The TLBO algorithm has been implemented to find the optimal switching angles of a single-phase 17-level cascaded H-bridge MLI (CHB-MLI). According to simulation results, the proposed method successfully solves non-linear equations for SHE, achieving a reduced THD of 4.31% while eliminating 5^{th}, 7^{th}, 11^{th}, 13^{th}, 17^{th}, 19^{th} and 23^{rd} harmonics. Furthermore, the THD values were compared with those reported in the existing literature obtained using different conventional modulation methods. The results indicated that the THD obtained using the TLBO algorithm was lower compared to the equal phase (EP), half equal phase (HEP), feed forward (FF) and half height (HH) methods. The proposed strategy can be further extended to reduce higher order harmonics. In addition, it can be implemented to other topologies.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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