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A Comparative Study on Performance of Fitness Functions for Harmonic Profile Improvement using Parameter-less AI Technique in Multilevel Inverter for Electrical Drives

Kaushal Bhatt[1,2] and Sandeep Chakravorty[1]

[1] Department of Electrical Engineering, Indus University, Ahmadabad, India
[2] Department of Electrical Engineering, Government Engineering College, Modasa, India

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Abstract: This article proposes the comparative investigation of harmonic profile improvement in the multi-phase multilevel inverter. For the proposed study, three-phase, seven-level cascaded H-bridge (CHB) multilevel inverter (MLI) is considered. Modulation of the stepped waveform output of the multilevel inverter is done using selective harmonic elimination (SHE) method. Many algorithms are proposed for solving the set of nonlinear transcendental trigonometric equations for selective harmonic elimination methods such as Genetic algorithm (GA), Particle Swarm Optimization (PSO) algorithm, and many more. Most of these techniques have controlling parameters, which need to be tuned while optimizing the fitness functions. The teaching learning-based optimization (TLBO) algorithm and JAYA algorithms are parameterless optimization techniques. Due to the lack of controlling parameters, these algorithms are most robust among the family of artificial intelligence (AI) techniques. TLBO algorithm has an added advantage of fast convergence compared to the JAYA algorithm. This advantage attracts most of the researchers to use TLBO in engineering Applications. A novel fitness function is proposed in this paper. The performance of the proposed fitness function is compared with two different popular fitness functions reviewed from various literature. A comparative investigation is carried out on these three fitness functions for controlling total harmonic distortion (THD) in a multilevel inverter. Throughout the article, a comparative exploration of lower order harmonics and THD profile with respect to modulation index is carried out for each fitness function. A most suitable fitness function is concluded after comparing total harmonic distortion profiles of each. In this article, a simulation study is carried out using the parameterless TLBO algorithm, and the performance is compared with the PSO algorithm. It is seen in this study that the proposed novel fitness function with the TLBO algorithm improves the harmonic profile by 17% compared to the PSO algorithm, producing the most optimum result.

Keywords: Multilevel Inverter, Cascaded H-bridge Inverter, Particle Swarm Algorithm, Teaching Learning-based Algorithm, ElectricDrives

1. INTRODUCTION

Electrical drives share a significant portion of the modern-day industry. Maturity in the development of Power electronic switches and converter-inverter technologies aid in the modern, variable speed, medium voltage high, and power drives [1], [2]. Among many options from the range of breeds in power inverters, the multilevel inverter has unique advantages. Merits of multilevel inverters are reviewed by many researchers. In multilevel inverters, Step-up transformers are nor needed, low switching frequency is possible if a particular switching scheme is applied, the input current is close to sinusoidal, reduced total harmonic distortion, low common-mode voltage, and low electromagnetic interference [3]. Multilevel inverters are typically divided into three groups: cascaded multistep inverter, flying capacitor multistep inverter, and diode clamped multistepinverter[4]. The cascaded H-bridge multilevel (CHB-MLI) inverter has become the most common of these three forms. CHB-MLI poses quick and easy manufacturing because of having a simple structure. It has a highly modular structure, requires very less amount of power handling and miscellaneous components, no need for diodes and flying capacitors. Since there are less power diodes and high-power capacitors in a cascaded H-

E-mail:kaushalbhatt.rs@indusuni.ac.in, deanacademics@indusuni.ac.in

bridge MLI, it takes up less room and costs less to manufacture than multilevel inverters with diode and capacitor clamping.[3], [5].

In Series H-bridge MLI, N H-bridges are cascaded, and the output waveform is synthesised by adding the outputs of each H-bridge. In this article, a seven-level CHB-MLI is considered because it is well suitable to eliminate the most damaging lower order harmonics like 5^{th}order, 7^{th}order and 11^{th} order harmonics in an electric drive system. Higher-level multilevel inverters, such as 9 level, 11 level inverters, increase the weight, cost, and control complexity with a small improvement in result. In comparison, low-level inverter such as 5 level inverter is not able to reduce the most damaging lower order harmonics. Figure 1 depicts a seven-level three-phase series H-bridge MLI. And the synthesized 7-level output waveform per phase is shown in Figure 2[6], [7]. The equation L = 2M+1, where M denotes total H-bridges used and L denotes number of steps, is used to calculate the total number of steps at the terminals of a specific CHB-MLI. In the present case, 3 H-bridges are series connected per phase, so that the total numbers of steps per phase at the terminals are 7. Hence a three-phase 7-level cascaded H-bridge inverter is produced by connecting three such phases in star connection. A set of nonlinear transcendental trigonometric equations can be used to describe the waveform depicted in Figure 2. [8]. Various modulation methods are applied to reduce the THD at the terminals, such as sine pulse width modulation, space vector modulation, and elimination of selected harmonics[9].

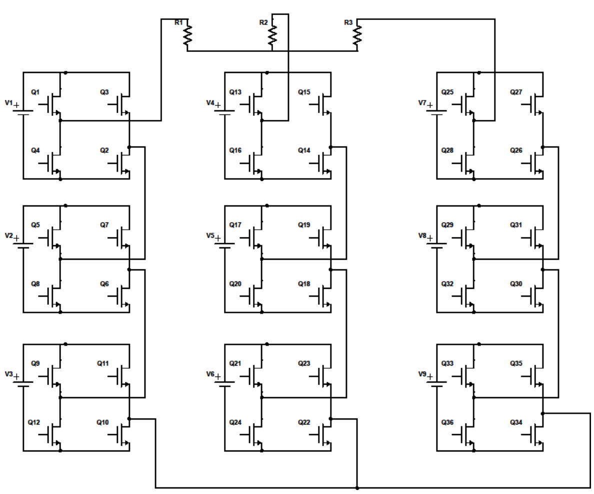

Figure 1. 3-Phase 7-Level cascaded H-bridge multilevel inverter

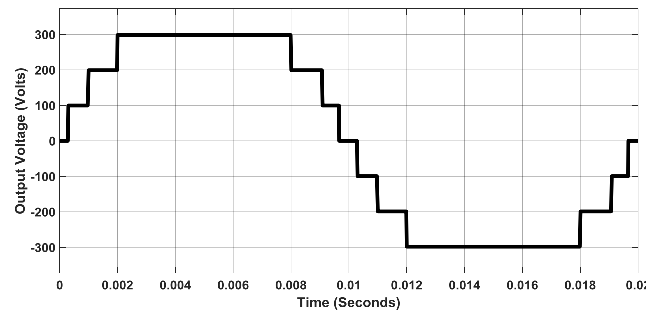

Figure 2. 1-Phase 7-Level synthesized waveform at the output of CHB-MLI

Out of these modulation methods, elimination of selective harmonics (SHE) has piquedthe interest of researches the most, as the proposed method is applicable with fundamental switching frequency and produces low switching losses and lowers electromagnetic interference in the drive system. Harmonic profile control is classified as follows: harmonic removal, harmonic alleviation, harmonic minimization, and total harmonic distortion. All these four categories of harmonic profile control are achieved with the help of a selective harmonic elimination method [3].

One can lessen the THD and improvise the harmonic profile by solving the set of the nonlinear transcendental trigonometric equation, which represents the output waveform of CHB-MLI [8]. By solving these equations, one can find the switching angles for firing the power switches. As shown in Figure 2, each H-bridge switches are fired at a particular angle and for a particular duration[6]–[9]. The solution of such an equation by a fundamental numerical method for example the Newton Raphson method is many times error sum as it needs accurate initial guess[10]. Another possibility of solving such a set of the equation is by using artificial intelligence (AI) algorithm techniques such as genetic algorithm[11], Particle swarm optimization algorithm[12], Gray wolf optimizer algorithm[13], Sine cosine algorithm based staircase modulation [14], gravity search optimization technique [15], BAT algorithm [16], simulated annealing algorithm and cuckoo search algorithm [17], imperialist competitive algorithm [18].

Most of the artificial algorithm techniques' optimization process [11]–[18] needs tuning of the controlling parameters. If not correctly tuned, the optimization cannot converge to the global minima and may give error while finding the firing angles. There are a few parameterless algorithms available such as teaching learning-based optimization algorithm [19] and JAYA algorithm [20]. Owing to their parameter less nature, they are most robust. TLBO algorithm has an added advantage of fast convergence compared to the JAYA algorithm [21].

This article introduces the use of the teaching learning-based optimization algorithm (TLBO), which has no controlling parameters; in other words, it is aparameterless AI technique[19], [22]. TLBO is a robust AI technique in terms of the solution to the nonlinear transcendental trigonometric equation as it does not need controlling parameters. Moreover, it is also seen in this article that the combination of proposed novel fitness function and TLBO algorithm gives far better results than various techniques represented in [23]–[25]. Various techniques in [23]–[25] include THD control using an alterable DC source, harmonic control using the nearest level modulation scheme, and THD controls directly applied to line voltage.

The rest of the proposed research article is arranged as follows: The method of elimination of selected harmonics (SHE) and the formation of fitness functions are eloborated in Section 2. Section 3 gives insight into the particle swarm optimization (PSO, with controlling parameters) and teaching learning-based optimization algorithm (TLBO, with no controlling parameters). Section 4 presents results and discussions; it discusses comparative efficacy of performance of each fitness function on harmonic profile improvement in relation to the modulation indices and also discusses the scope of exploration of modulation index. Section 5 presents the conclusion on the optimum fitness function that should be used for further research by any researcher, followed by references.

2. Selective Harmonic Elimination and Formulation of Fitness Functions

Selective harmonic elimination modulation technique has gained interest from many researchers as it can control the harmonics in multilevel inverter using fundamental switching frequency [26]. The selective harmonic elimination technique has a rich bunch of advantages; many of the advantages are as follows [27]:

- Power quality is high with a low value of modulation index.
- Filter size at the output is negligible as the numbers of level increases.
- Higher voltage gain.
- The three-phase system has added advantage of the natural elimination of triplen harmonics.
- Low electromagnetic interference.
- Pre calculated angles can be stored in the lookup table for online application.

A. *Set of Nonlinear Transcendental Equations Representing the Output Stepped Voltage*

The output of the proposed 7-level inverter can be represented with the help of the Fourier series expansion, as given in equation 1.

$$v(wt) = a_0 + \sum_{n=1}^{\infty}\left[a_n \cos(nwt) + b_n \sin(nwt)\right] \quad (1)$$

In this article, the load on the 3-phase inverter is considered to be balanced. In the balanced condition, the waveform, as shown in Figure 2, can be considered as quarter-wave symmetrical. In equation 1, The DC component a0, odd and even terms of cosine component, as well as even terms of sine components are zero. The modified equation after, all zero components removed, is given in equation 2. Equation 3 gives the value of the component b_n of equation 1.

$$v(wt) = \sum_{n=1,3,5,....}^{\infty} b_n \sin(nwt) \quad (2)$$

$$b_n = \frac{4V_{DC}}{n\pi}\left[\cos(n\alpha_1) + \cos(n\alpha_2) + \cos(n\alpha_3)\right] \quad (3)$$

The final modified equation of the terminal voltage is given in equation 4 [26], [27]. It should be noted that the three-phase structure cancels all triplen harmonics in the 3-phase system.

$$v(wt) = \sum_{n=1,3,5,....}^{\infty} \frac{4V_{DC}}{n\pi}\left[\cos(n\alpha_1) + \cos(n\alpha_2) + \cos(n\alpha_3)\right]\sin(nwt)$$
(4)

A general set of the nonlinear transcendental trigonometric equation can be prepared from equation 1 to 4 as presented in equation 5 to 8 shown below,

$$\cos(\alpha_1) + \cos(\alpha_2) + \cos(\alpha_3) = 3M \quad (5)$$

$$\cos(5\alpha_1) + \cos(5\alpha_2) + \cos(5\alpha_3) = 0 \quad (6)$$

$$\cos(7\alpha_1) + \cos(7\alpha_2) + \cos(7\alpha_3) = 0 \quad (7)$$

$$\cos(11\alpha_1) + \cos(11\alpha_2) + \cos(11\alpha_3) = 0 \quad (8)$$

Where,
M denotes the modulation indice values, defined as the proportion of desired fundamental voltage per total available voltage per phase.

$$M = \frac{V_1}{\left(\frac{4V_{DC}}{\pi}\right)} \quad (9)$$

Where, V_1 = desired fundamental voltage,

V_{DC} = DC voltage applied to each H-bridge inverter.

α_1, α_2 and α_3 = firing angles of power electronic switches per quarter cycle.

Also, $0° < \alpha_1, \alpha_2, \alpha_3 < \frac{\pi}{2}$

The range of α_1, α_2 and α_3 is from 0º to 90° for a quarter-wave symmetrical waveform.

From the above set of equations, various researchers have proposed various fitness functions that are treated with artificial intelligence algorithms, and firing angles for the power switches are found. The following subsections discuss three different fitness functions. In subsection B and C fitness function, F1 and F2 are reviewed from various literature. While in subsection D, a novel fitness function F3 is derived by the authors in this paper.

B. Formulation of Fitness Function F1(α), strategy 1

Many researchers have formulated the Fitness function using a set of three equations given in equations 10 to 12 [28], [29].

$$h_1 = \cos(\alpha_1) + \cos(\alpha_2) + \cos(\alpha_3) \quad (10)$$

$$h_5 = \cos(5\alpha_1) + \cos(5\alpha_2) + \cos(5\alpha_3) \quad (11)$$

$$h_7 = \cos(7\alpha_1) + \cos(7\alpha_2) + \cos(7\alpha_3) \quad (12)$$

Here h_1 indicates fundamental component, h_5 and h_7 represent fifth and seventh harmonics in output voltage. Fitness Function F1 (α) is given in equation 13.

$$F1(\alpha) = (h_1 - 3M)^2 + (h_5)^2 + (h_7)^2 \quad (13)$$

Where, M = Modulation index (given in equation 9)

h_1 = Fundamental component

h_5 = 5^{th} harmonic component

h_7 = 7^{th} harmonic component

The fitness function F1(α), given in equation 13, uses three equations 10 to 12. Equation 10 is used to keep the fundamental voltage value up to the required level decided by the modulation index M. equation 11 and 12 are used to minimize the 5th and 7th harmonic. As such, any harmonic order can be eliminated in this case, but the magnitude of lower order harmonics is more damaging, so 5th and 7th order harmonics are controlled. Moreover, it should be mentioned that function F1 (α) cannot eliminate 11^{th} order harmonic.

C. Formulation of Fitness Function F2(α), strategy 2

In many research papers, a formula of total harmonic distortion is derived from the fundamental equation of the THD, as given in equation 14 [30], [31]. Fitness Function F2 (α) is given in equation 15.

$$THD = \sqrt{\left[\left[\left(\frac{\pi}{4}\right) \times \frac{(\alpha_2 - \alpha_1) + 4(\alpha_3 - \alpha_2) + 9(\frac{\pi}{2} - \alpha_3)}{((\cos\alpha_1) + (\cos\alpha_2) + (\cos\alpha_3))^2}\right] - 1\right]} \quad (14)$$

$$F2(\alpha) = (10 \times |h_1 - 3M|) + THD \quad (15)$$

Where, M = Modulation index.

h_1 = Fundamental component

α_1, α_2 and α_3 = firing angles of power electronicswitches per quarter cycle.

In equation 15, fundamental harmonic is considered from equation 10. In the equation of fitness function F2(α), a factor of 10 is multiplied with the fundamental harmonic to increase the weightage of fundamental components and keep it up to the required level decided by the modulation index [30], [31].

D. Formulation of Fitness Function F3(α), strategy 3

This article proposes Strategy 3 for the novel Fitness function F3 (α). The proposed fitness function uses equations 5 to 8. In this case, THD is defined in equation 16. The formulation of the proposed fitness function is given in equation 17.

$$THD = \sqrt{\left(\frac{h_5}{5}\right)^2 + \left(\frac{h_7}{7}\right)^2 + \left(\frac{h_{11}}{11}\right)^2} \quad (16)$$

$$F3(\alpha) = (|h_1 - 3M|) + THD \quad (17)$$

Where, M = Modulation index.

h_1 = Fundamental component

h_5 = 5^{th} harmonic component

h_7 = 7^{th} harmonic component

h_{11} = 11^{th} harmonic component

Among the fitness-function strategies discussed so far, strategy 3 presenting proposed novel fitness-function F3(α), gives the most optimized result when treated with AI techniques. As discussed in section 4, the angles available from the MATLAB code is fed to the MATLAB-Simulink model, and Total harmonic distortion in line voltage are compared for each strategy. The following section discusses two well-known algorithms, PSO and TLBO.

3. Artificial Intelligent Algorithm

In this article, two popular algorithms are studied, one of them is PSO [12], and the other is TLBO [22]. PSO is an algorithm with controlling parameters with obvious disadvantages of controlling them. TLBO is a robust and parameterless algorithm. The following subsection discusses both the algorithms.

A. Particle Swarm Optimization Algorithm (PSO)

Particle swarm optimization was introduced by Kennedy and Eberhart in 1995 [32], [33]. In particle swarm optimization, the initial random swarm of the particle is created as it is a metaheuristic algorithm. In the swarm of the particles, each particle shows a possible candidate solution. In PSO, each particle moves towards the final solution. The velocity of their movement is updated as the iterations continue. Equations 18 and 19 decide particles' intermediate velocity and position, respectively. Equation 20 represents the weightage of the particles in each iteration. It should be noted that the weightage of the particle increases, and the steps size reduces as the iteration increases.

$$V_j(i) = \omega V_j(i-1) + c_1 r_1 \left[P_{best,j} - \alpha_j(i-1)\right] + c_2 r_2 \left[G_{best,j} - \alpha_j(i-1)\right] \quad (18)$$

$$\alpha_j(i) = \alpha_j(i-1) + V_j(i) \quad (19)$$

$$\omega(i) = \omega_{\max} - \left(\frac{\omega_{\max} - \omega_{\min}}{i_{\max}}\right) \times i \quad (20)$$

Where,

$j = 1, 2, \dots\dots\dots N$ (i.e. if J = 1, 1st particle)

i = iteration number,

$V_j(i) =$ The intermediate velocity of the jth particle in ith iteration

$X_j(i) =$ The intermediate position of the jth particle in ith iteration

$\omega_{\max}, \omega_{\min}$ = The initial and final weight of the particles,

C_1 and C_2 = individual and group learning rates.

It is worth noteingthat α in the fitness equations components is obtained from the α of equation 19 after the MATLAB code runs for the total number of iterations.

The flow chart in Figure 3 presents the workflow to be followed at the time of producing software code for the PSO algorithm. It accommodates all the steps involved in preparing a code.

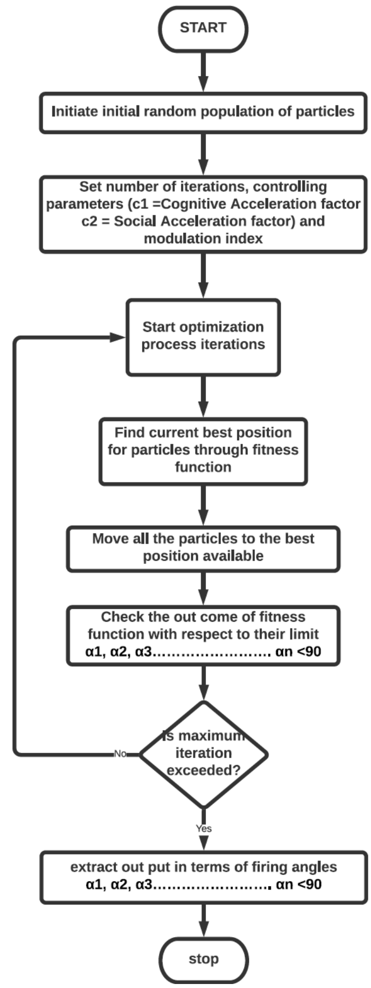

Figure 3. Algorithm flow chart for particle swarm optimization algorithm

B. Teaching Learning Based Optimization Algorithm (TLBO)

A teacher-learner based optimizertechnique was proposed by Rao et al.[19]. It is a robust parameter less algorithm. The TLBO algorithm is divided in two phases, namely the teaching phase and the learning phase. A class of students as variables is created where the most knowledgeable student acts as a teacher. Each student in the class represents a possible candidate solution. The variables of design are offered as the subjects to the students. The knowledge of each student is the fitness function value. The best student acts as the teacher with the optimum value of fitness function. Procedure for the TLBO algorithm in teaching-learning phase is explained as below:

a) Teaching Phase

In this phase mean of swarm of students' knowledge is found out for each subject (design variable). In the teaching stage, the teacher upgrades the understanding of students, according to student's grasping capabilities. Equation 21 represents the knowledge transfer process.

$$\alpha_{new,j}^{k} = \alpha_{j}^{k} + r\left(Th^{k} - M^{k-1}\right) \qquad (21)$$

Where,

α_{j}^{k} = switching angle vector of the j[th] student in iteration k.

Th^{k} = The best switching angle vector acts as a teacher.

$\alpha_{new,j}^{k}$ = new switching angle vector after the teaching process, it only gets approved if it is improved than the previous value.

b) Learning Phase

After the teaching phase, the learner phase starts. Students try to interact with each other randomly because many of the students might not have grasped from the teacher in the teaching phase. When two students randomly meet to discuss the topic, knowledge transfer takes place from knowledgeable students to the knowledge-seeking student. The knowledge transfer process is expressed by equations 22 and 23. In Random manor, two students say α_{x}^{k} , and α_{y}^{k} meet for knowledge transfer, in the k[th] iteration.

If $F\left(\alpha_{x}^{k}\right) > F\left(\alpha_{y}^{k}\right)$ i.e., α_{x}^{k} is more knowledgeable, Equation 22 transfers the knowledge from bright students to the weak student.

$$\alpha_{new,j}^{k} = \alpha_{j}^{k} + r\left(\alpha_{x}^{k} - \alpha_{y}^{k}\right) \qquad (22)$$

If $F\left(\alpha_{y}^{k}\right) > F\left(\alpha_{x}^{k}\right)$, i.e., α_{y}^{k} is more knowledgeable. Equation 23 transfers the knowledge, from bright students to the weak student.

$$\alpha_{new,j}^{k} = \alpha_{j}^{k} + r\left(\alpha_{y}^{k} - \alpha_{x}^{k}\right) \qquad (23)$$

It is worth noting that, α in the fitness equation components corresponds to $\alpha_{new,j}^{k}$, which is taken from either equation 22 or 23 after the MATLAB code runs for the total number of iterations.

Steps for implementation of MATLAB code for the TLBO algorithm can be derived from the flowchart given in Figure 4.

4. RESULTS AND DISCUSSION

In this section, all three fitness functions are treated with PSO and TLBO algorithms. A total of 100 agents are taken in PSO and TLBO MATLAB codes. Each code is run with 200 iterations, moreover to check the accuracy of code, both the code is run 10 times. In each trial, both PSO and TLBO codes have proven consistency. The upper and lower bounds are set to 0° and 90° because the waveform has quarter-wave symmetry. For each fitness-function, the following points of comparison are presented for the proposed study.

- Firing angles figured out using PSO and TLBO algorithms.
- Lower order harmonics are compared for PSO and TLBO algorithms.
- THD comparison presented for PSO and TLBO algorithms.
- Data are tabulated for various performance parameters between PSO and TLBO.
- FFT (MATLAB- Fast Fourier Transform) window is presented for the minimum THD v/s modulation index for the optimum case.
- The line voltage waveform is presented for the minimum THD v/s modulation index.

Subsection A, B, and C investigates the above points of comparison for fitness function F1, fitness function F2, and the proposed novel fitness function F3, respectively.

A. *Comparative Investigation on Fitness function F1(α)*

In this case, Fitness-function F1(α), as given in equation 13, gives firing angles for modulation index values 0.4 to 1.2. In thepresent case, modulation indices extension beyond the value of 1 is possible, which is considered as a good sign of a particular fitness function performance. The following figures describe further the performance of fitness function F1.

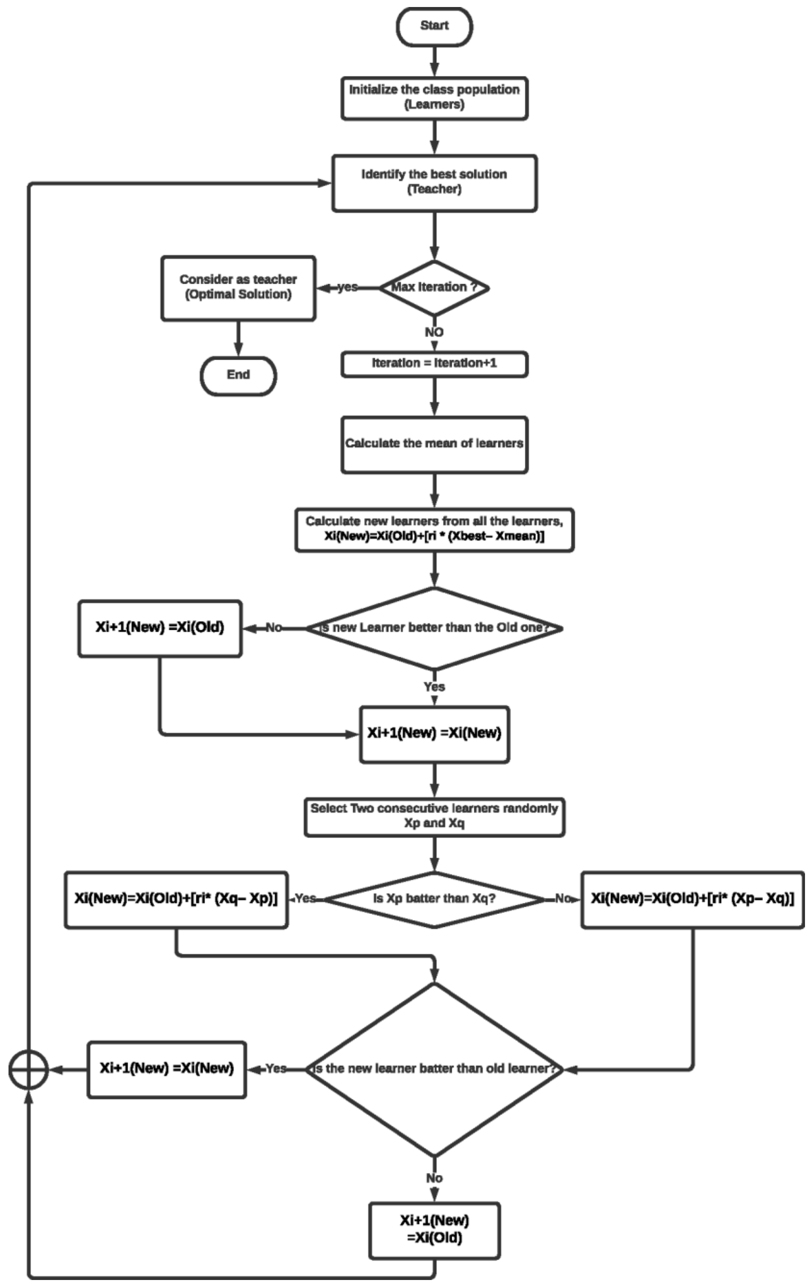

Figure 4. Algorithm flow chart for teaching learning-based optimization algorithm

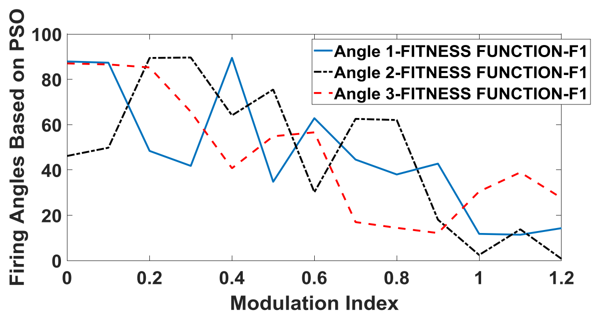

Figure 5. Firing angles based on PSO algorithm for fitness function-F1

Figure 5 shows the relation between firing angles obtained using the PSO algorithm versus the Modulation index. As seen from Figure 5, the utilizable firing angles are available from the modulation index value 0.4 to 1.2.

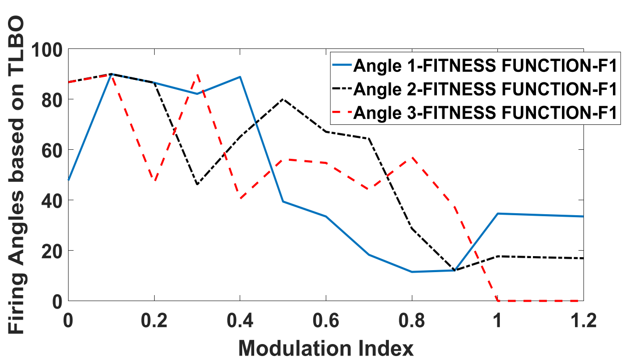

Figure 6. Firing angles based on TLBO algorithm for fitness function-F1

Figure 6 shows the relation between firing angles obtained using the TLBO algorithm versus the Modulation index. As seen from Figure 6, the utilizable firing angles are available from the modulation index value 0.4 to 1.2.

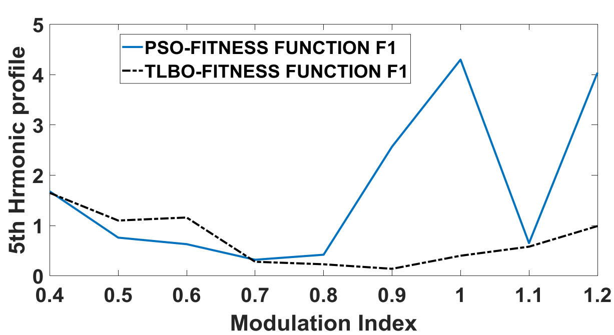

Figure 7. Line voltage 5th harmonic profile comparison based on PSO and TLBO algorithms for fitness function- F1

Figure 7 shows the relation between the 5th Harmonics profile of the modulation indices versus the line voltage. The PSO and TLBO methods produce firing angles with modulation indices ranging from 0.4 to 1.2, The 5th harmonic profile is also obtained for the range of modulation indices from 0.4 to 1.2.

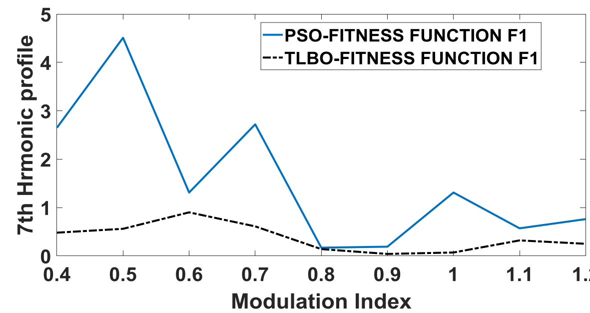

Figure 8. Line voltage 7th harmonic profile comparison based on PSO and TLBO algorithms for fitness function- F1

Figure 8 shows the relation between the 7th Harmonics profile of the modulation indices versus the line voltage obtained using PSO and TLBO algorithm. The 7th harmonic profile ranges from 0.4 to 1.2.

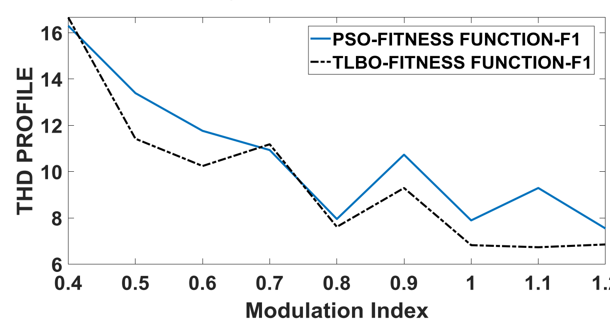

Figure 9. Line voltage THD profile comparison, based on PSO and TLBO algorithms for fitness function- F1

Figure 9 shows the relation between THD profiles of line voltage versus modulation index. It is concluded from Figures 5 to 9 that the fitness function-F1 gives better results with the TLBO algorithm compared to the PSO algorithm.

B. Comparative Investigation on Fitness Function F2(α)

In this case, Fitness-function F2 (α), as given in equation 15, gives firing angles for modulation index values 0 to 1. In this case, the modulation index extension is not possible beyond the value of 1. That means over modulation is not possible with this fitness function. The following figures describe further the performance of fitness function F2.

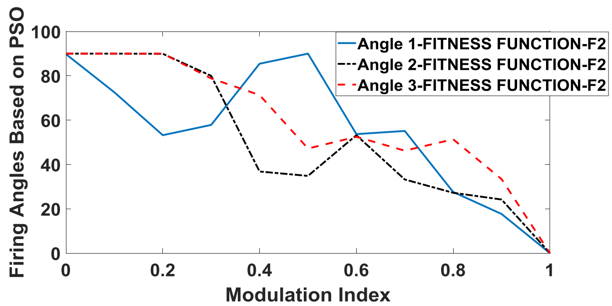

Figure 10. Firing angles based on PSO algorithm for fitness function-F2

Figure 10 shows the relation between firing angles obtained using the PSO algorithm versus the Modulation index. As seen from Figure 10, the firing angles are available from the modulation index value 0 to 1.

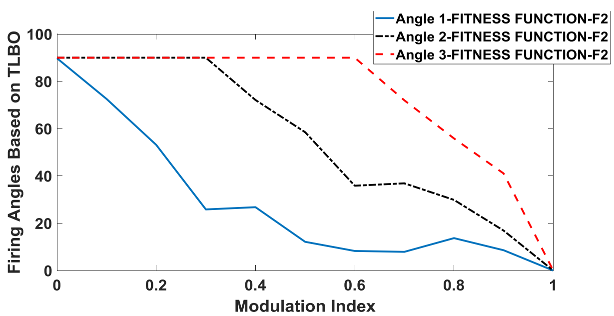

Figure 11. Firing angles based on TLBO algorithm for fitness function-F2

Figure 11 shows the relation between firing angles obtained using the TLBO algorithm versus the Modulation index. As seen from Figure 11, the firing angles are available from the modulation index value 0 to 1, but the utilizable firing angles are obtained for the modulation indices rangingfrom 0.7 to 0.9. The utilizable line voltage THD profile is available only for the modulation indices rangingfrom 0.7 to 0.9, as shown in Figure 12.

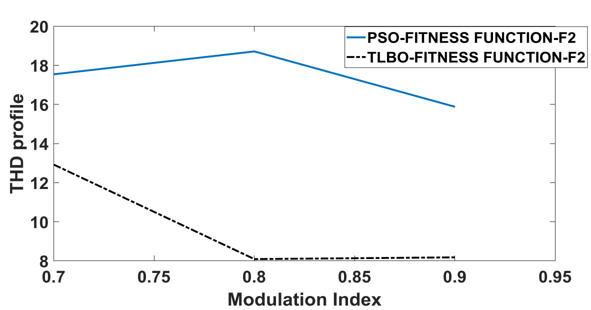

Figure 12. Line voltage, THD profile comparison, based on PSO and TLBO algorithms for fitness function-F2

It is concluded from Figures 10 to 12 that the fitness function-F2 gives better results with the TLBO algorithm compared to the PSO algorithm.

C. Comparative Investigation on Fitness Function F3(α)

In this case, the proposed novel Fitness-function F3(α) as given in equation 17, which gives firing angles for modulation index values 0.4 to 1.2. It is the broadest range of modulation index, with the most optimum values of firing angles among three fitness functions. In this case, the modulation index extension is possible above the value of 1, which is considered as a good sign of a particular fitness function performance. The following figures describe further the performance of the proposed novel fitness function F3.

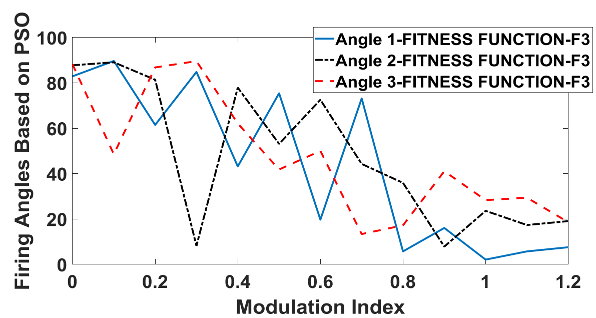

Figure13. Firing angles based on PSO algorithm for fitness function-F3

Figure 13 shows the relation between firing angles obtained using the PSO algorithm versus the Modulation index. As seen from Figure 13, the utilizable firing angles are available from the modulation index value 0.4 to 1.2.

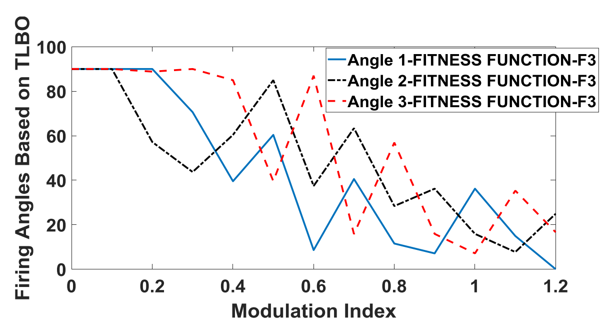

Figure 14. Firing angles based on TLBO algorithm for fitness function-F3

Figure 14 shows the relation between firing angles obtained using the TLBO algorithm versus the Modulation index. As seen from Figure 14, the utilizable firing angles are available from the modulation index value 0.4 to 1.2.

Figure 15, 16, and 17 shows the relation between the 5^{th}, 7^{th} order, and 11^{th} order line voltage Harmonics and modulation indices. As the PSO and TLBO algorithms give firing angles in the modulation indices rangingfrom 0.4 to 1.2. The 5th, $7^{th,}$ and 11^{th} harmonic profile is also obtained for the modulation indices ranging from 0.4 to 1.2

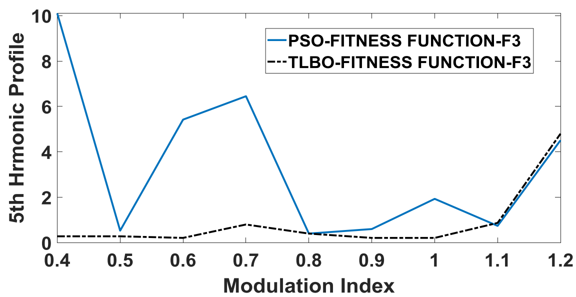

Figure 15. Line voltage 5th harmonic profile comparison based on PSO and TLBO algorithms for fitness function-F3

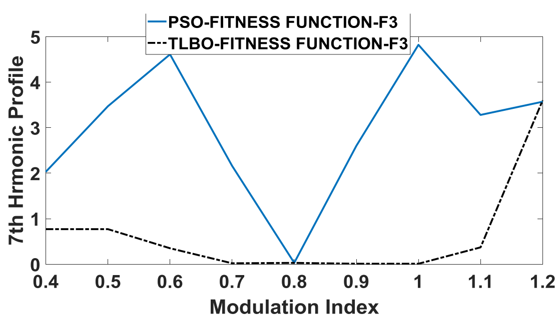

Figure 16. Line voltage 7th harmonic profile comparison based on PSO and TLBO algorithms for fitness function-F3

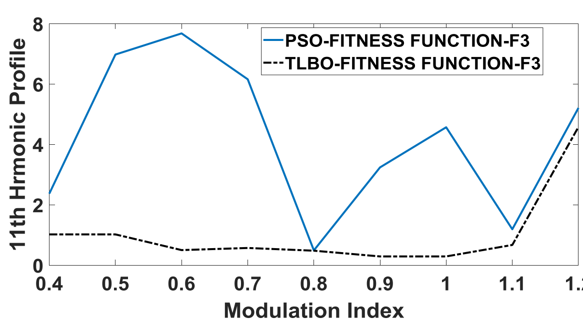

Figure 17. Line voltage 11th harmonic profile comparison based on PSO and TLBO algorithms for fitness function-F3

Figure 18 shows the relation between THD profiles versus the modulation index. It is concluded from Figures 13 to 18 that the proposed novel fitness function-F3 gives better results with the TLBO algorithm compared to the PSO algorithm.

A detailed comparison of the performance of fitness functions F1, fitness functions F2, and proposed novel fitness functions F3 is given in table 1. Results in Figures, 19 to 22, show the most optimized results available from the novel fitness function F3 using TLBO and PSO.

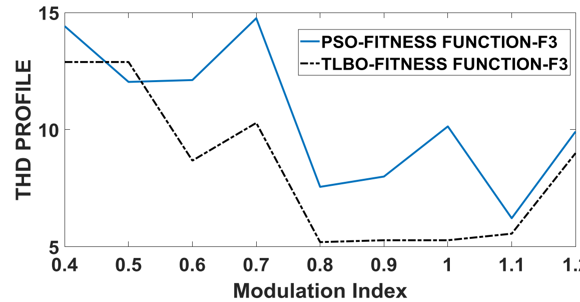

Figure 18. Line voltage THD profile comparison, based on PSO and TLBO algorithms for fitness function-F3

Figure 19 depicts the 7-level output terminal line voltage waveform with 0.8 modulation indices. using the TLBO algorithm and proposed novel fitness function F3. The FFT profile is shown in figure 20 for the waveform in Figure 19. It is to be noted that fitness function F3 with the TLBO algorithm gives minimum THD at a 0.8 modulation indices. Figure 21 depicts the line voltage waveform of a 7-level output terminal voltage at 1.1 modulation indices using the PSO algorithm and the proposed novel fitness function F3, using the PSO algorithm and proposed novel fitness function F3. The FFT profile is shown in figure 22 for the waveform in Figure 21. It is to be noted that fitness function F3 with the PSO algorithm gives minimum THD at a modulation index value of 1.1.

The THD obtained using a combination of TLBO and fitness function F3 is 5.2 %, while THD obtained using PSO and fitness function F3 is 6.22. Which means TLBO improves results by 17% compared to PSO. Figures 19 to 22, confirm the data set given in Table 1, about the superiority of the TLBO methodcompared to the PSO method for the proposed novel fitness function F3.

5. Conclusion

In this article, three different fitness functions are compared for their performance inrelation to reduction of total harmonic distortion. For optimization of the fitness function, particle swarm optimizer algorithm and teaching-learning based optimizer algorithms are used. It is observed in the optimization process that, in algorithms such as PSO having controlling parameters are required to tune the parameter; otherwise, the results are not optimal. The tuning of control parameters is always a time-consuming task that cannot be applied to online power electronics drive applications. TLBO is introduced in this article as a parameterless optimization method. Due to the lack of controlling parameters, these types of algorithms are robust and perform optimum optimization. The TLBO algorithm also does not need time for controlling parameters in the online applications of Power electronics drives.

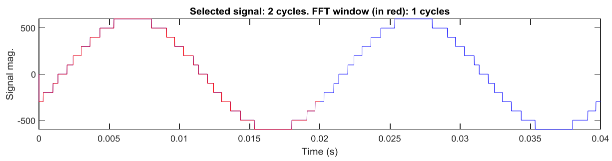

Figure 19. Line voltage waveform for M = 0.8, and fitness function-3 for 3-phase, 7-level CHB-MLI using TLBO

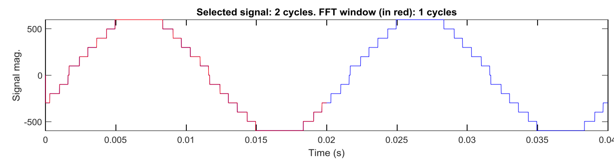

Figure 21. Line voltage waveform for M = 1.1, and fitness function-3 for 3-Phase, 7-level CHB-MLI using PSO.

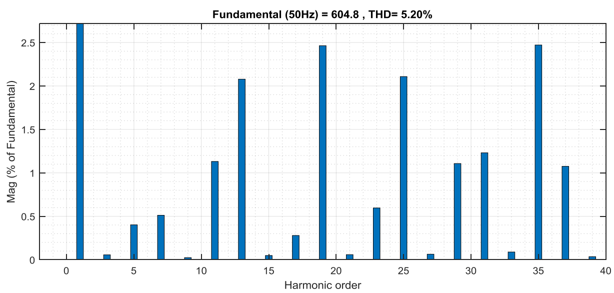

Figure 20. FFT window for line voltage waveform for M = 0.8, and fitness function-3 for 3-Phase, 7-level CHB-MLI using TLBO

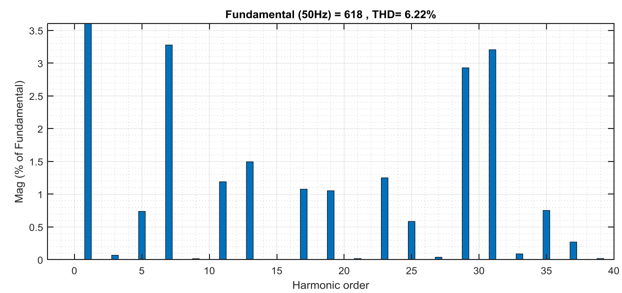

Figure 22. FFT window for line voltage waveform for M = 1.1, and fitness function-3 for 3-Phase, 7-level CHB-MLI using PSO.

TABLE I. COMPARATIVE ANALYSIS OF FITNESS FUNCTION-F1, FITNESS FUNCTION-F2, AND FITNESS FUNCTION-F3

Algorithm Performance Parameters		**Value**		
		Fitness Function -F1	***Fitness Function -F2***	***Fitness Function -F3 (Proposed novel fitness function)***
PSO	Minimum line voltage THD value	7.54	15.88	6.22
	Modulation index for minimum line voltage THD value	1.2	0.9	1.1
	Number of iterations	200	200	200
	Number of particles (Agents)	100	100	100
	Upper and lower bound	0º to 90°	0º to 90°	0º to 90°
	Number of trial for PSO code with 200 iterations	10	10	10
	Time for running the code (seconds)/trial	0.3	0.3	0.35
TLBO	Minimum line voltage THD value	6.73	8.09	**5.2**
	Modulation index for minimum line voltage THD value	1.1	0.8	0.8
	Number of iterations	200	200	200
	Number of Students (Agents)	100	100	100
	Upper and lower bound	0º to 90°	0º to 90°	0º to 90°
	Number of trial for TLBO code with 200 iterations	10	10	10
	Time for running the code (seconds)/trial	0.3	0.3	0.34

It is also observed in section 4 that TLBO produces batter results for all three fitness functions.

Performance of the three fitness functions, namely fitness function-F1, fitness function-F2, and the proposed novel fitness function-F3 for harmonic profile improvement, is observed by optimizing them with PSO and TLBO algorithm. A detailed comparison of the performance of the three fitness functions is seen in table 1. It is seen that the suggestednew fitness function-F3 gives the most optimized result out of the three fitness functions. Further For a 0.8 modulation indices, the Fitness function-F3 produces a THD value of 5.2, which is below IEEE 519-2014 standards for the three-phase system.

It can be concluded after the comparison of the performance of three fitness functions that proposed novel fitness function-F3 can be used in online power electronics drive applications. It is also recommended to use parameterless AI techniques such as TLBO in control applications of electrical drive systems.

Declaration of Competing Interest

The authors declare that they have no established conflicting financial interests or personal dealings that may have influenced the study presented in this article.

References

[1] A. Chitra, W. R. Sultana, J. Vanishree, S. Sreejith, S. Jose, and A. J. Pulickan, "Performance Comparison of Multilevel Inverter Topologies for Closed Loop v/f Controlled Induction Motor Drive," Energy Procedia, vol. 117, pp. 958–965, 2017, doi: 10.1016/j.egypro.2017.05.216.

[2] R. Uthirasamy, U. S. Ragupathy, and R. Naveen, "Structure of 15-level sub-module cascaded H-bridge inverter for speed control of AC drive applications," *Int. J. Power Electron. Drive Syst.*, vol. 5, no. 3, pp. 404–414, 2015, doi: 10.11591/ijpeds.v5.i3.pp404-414.

[3] K. Bhatt and S. Chakravorty, "Mitigation of Harmonics from Output of Cascaded H Bridge Multi Level Inverter Using SHE PWM and AI Technique: A Review," *Recent Adv. Electr. Electron. Eng. (Formerly Recent Patents Electr. Electron. Eng.*, vol. 13, no. 1, pp. 1–17, 2020, doi: 10.2174/2213111607666200214121450.

[4] A. Marzoughi, R. Burgos, D. Boroyevich, and Y. Xue, "Investigation and comparison of cascaded H-bridge and modular multilevel converter topologies for medium-voltage drive application," *IECON Proc. (Industrial Electron. Conf.*, pp. 1562–1568, 2014, doi: 10.1109/IECON.2014.7048710.

[5] F. Khoucha, S. M. Lagoun, K. Marouani, A. Kheloui, and M. E. H. Benbouzid, "Hybrid cascaded H-bridge multilevel-inverter induction-motor-drive direct torque control for automotive applications," *IEEE Trans. Ind. Electron.*, vol. 57, no. 3, pp. 892–899, 2010, doi: 10.1109/TIE.2009.2037105.

[6] B. Ozpineci, L. M. Tolbert, and J. N. Chiasson, "Harmonic optimization of multilevel converters using genetic algorithms," *IEEE Power Electron. Lett.*, vol. 3, no. 3, pp. 92–95, 2005, doi: 10.1109/LPEL.2005.856713.

[7] N. M. Yazdani, A. Y. Sequerloo, and M. S. Panahi, "Reduction of Harmonic in Multilevel Inverters using FA and LAFA ALGORITHMS," *J. Basic. Appl. Sci. Res*, vol. 3, no. 1s, pp. 130–135, 2013.

[8] M. H. Etesami, N. Farokhnia, and S. H. Fathi, "A method based on Imperialist Competitive Algorithm (ICA), aiming to mitigate harmonics in multilevel Inverters," *2011 2nd Power Electron. Drive Syst. Technol. Conf. PEDSTC 2011*, pp. 32–37, 2011, doi: 10.1109/PEDSTC.2011.5742441.

[9] Z. Gong, Q. Cui, X. Zheng, P. Dai, and R. Zhu, "An improved imperialist competitive algorithm to solve the selected harmonic elimination pulse-width modulation in multilevel converters," *Energies*, vol. 11, no. 11, 2018, doi: 10.3390/en11113080.

[10] L. Manai, M. Dabboussi, F. Armi, and M. Besbes, "Cascaded multilevel inverter control considering low harmonic content based on comparison study between firefly and Newton Raphson Algorithm," *4th Int. Conf. Control Eng. Inf. Technol. CEIT 2016*, pp. 16–18, 2017, doi: 10.1109/CEIT.2016.7929093.

[11] H. Karaca and E. Bekta, "GA based selective harmonic elimination for multilevel inverter with reduced number of switches," *Lect. Notes Eng. Comput. Sci.*, vol. 2219, pp. 204–209, 2015.

[12] H. Taghizadeh and M. Tarafdar Hagh, "Harmonic elimination of cascade multilevel inverters with nonequal dc sources using particle swarm optimization," *IEEE Trans. Ind. Electron.*, vol. 57, no. 11, pp. 3678–3684, 2010, doi: 10.1109/TIE.2010.2041736.

[13] P. Q. Dzung, N. T. Tien, N. DInh Tuyen, and H. H. Lee, "Selective harmonic elimination for cascaded multilevel inverters using Grey Wolf Optimizer algorithm," *9th Int. Conf. Power Electron. - ECCE Asia "Green World with Power Electron. ICPE 2015-ECCE Asia*, pp. 2776–2781, 2015, doi: 10.1109/ICPE.2015.7168164.

[14] P. Mishra and A. Mahesh, "Sine cosine algorithm based staircase modulation for cascaded H-bridge inverter," *Proc. 3rd Int. Conf. Electron. Commun. Aerosp. Technol. ICECA 2019*, pp. 914–919, 2019, doi: 10.1109/ICECA.2019.8822115.

[15] J. V. Rao and A. Mahesh, "Firing angle optimization of seven-level cascaded H-bridge multilevel inverter with un-equal DC sources using GSA approach," *2016 IEEE 7th Power India Int. Conf. PIICON 2016*, 2017, doi: 10.1109/POWERI.2016.8077389.

[16] K. Ganesan, K. Barathi, P. Chandrasekar, and D. Balaji, "Selective Harmonic Elimination of Cascaded Multilevel Inverter Using BAT Algorithm," *Procedia Technol.*, vol. 21, pp. 651–657, 2015, doi: 10.1016/j.protcy.2015.10.078.

[17] N. V. Kumar, V. K. Chinnaiyan, M. Pradish, and M. S. Divekar, "Selective harmonic elimination: An comparative analysis for seven level inverter," *2016 IEEE Students' Technol. Symp. TechSym 2016*, pp. 157–162, 2017, doi: 10.1109/TechSym.2016.7872674.

[18] A. Ajami, M. R. J. Oskuee, A. Mokhberdoran, and H. Shokri, "Selective harmonic elimination method for wide range of modulation indexes in multilevel inverters using ICA," *J. Cent. South Univ.*, vol. 21, no. 4, pp. 1329–1338, 2014, doi: 10.1007/s11771-014-2070-9.

[19] R. V. Rao and V. Patel, "An improved teaching-learning-based optimization algorithm for solving unconstrained optimization problems," *Sci. Iran.*, vol. 20, no. 3, pp. 710–720, 2013, doi: 10.1016/j.scient.2012.12.005.

[20] R. Venkata Rao, "Jaya: A simple and new optimization algorithm for solving constrained and unconstrained optimization problems," *Int. J. Ind. Eng. Comput.*, vol. 7, no. 1, pp. 19–34, 2016, doi: 10.5267/j.ijiec.2015.8.004.

[21] R. Buddala and S. S. Mahapatra, "Improved teaching–learning-based and JAYA optimization algorithms for solving flexible flow shop scheduling problems," *J. Ind. Eng. Int.*, vol. 14, no. 3, pp. 555–570, 2018, doi: 10.1007/s40092-017-0244-4.

[22] H. D. Mehta and R. M. Patel, "Comparative Performance Analysis of Swarm and Intelligent Evolutionary Techniques for Optimal Design of Distribution Transformer," vol. 5, no. 3, pp. 46–58, 2015.

[23] M.-R. Jannati-Oskuee, "Optimization of Line voltage THD in Multilevel Inverter"s with Alterable DC Links using TLBO Optimization of Line voltage THD in Multilevel Inverter's with Alterable DC Links using TLBO," no. December, 2017.

[24] R. Khamooshi and J. S. Moghani, "Comprehensive harmonic optimization in cascaded h-bridge multilevel inverters using variable DC sources," *PEDSTC 2014 - 5th Annu. Int. Power Electron. Drive Syst. Technol. Conf.*, no. Pedstc, pp. 249–254, 2014, doi: 10.1109/PEDSTC.2014.6799380.

[25] R. Kumar and D. Thangavelusamy, "A modified nearest level modulation scheme for a symmetric cascaded H-bridge inverter," *Gazi Univ. J. Sci.*, vol. 32, no. 2, pp. 471–481, 2019.

[26] M. A. Memon, S. Mekhilef, M. Mubin, and M. Aamir, "Selective harmonic elimination in inverters using bio-inspired intelligent algorithms for renewable energy conversion applications: A review," *Renew. Sustain. Energy Rev.*, vol. 82, no. September 2017, pp. 2235–2253, 2018, doi: 10.1016/j.rser.2017.08.068.

[27] M. S. A. Dahidah, G. Konstantinou, and V. G. Agelidis, "A Review of Multilevel Selective Harmonic Elimination PWM: Formulations, Solving Algorithms, Implementation and Applications," *IEEE Trans. Power Electron.*, vol. 30, no. 8, pp. 4091–4106, 2015, doi: 10.1109/TPEL.2014.2355226.

[28] S. S. A. Ali, R. Kannan, and M. S. Kumar, "Exploration of Modulation Index in Multilevel Inverter using Particle Swarm Optimization Algorithm," *Procedia Comput. Sci.*, vol. 105, no. December 2016, pp. 144–152, 2017, doi: 10.1016/j.procs.2017.01.194.

[29] S. Kundu, A. D. Burman, S. K. Giri, S. Mukherjee, and S. Banerjee, "Comparative study between different optimisation techniques for finding precise switching angle for SHE-PWM of three-phase seven-level cascaded H-bridge inverter," *IET Power Electron.*, vol. 11, no. 3, pp. 600–609, 2018, doi: 10.1049/iet-pel.2017.0530.

[30] J. Olamaei and M. Karimi, "Total harmonic distortion minimisation in multilevel inverters using the teaching–learning-based optimisation algorithm," *Int. J. Ambient Energy*, vol. 39, no. 3, pp. 264–269, 2018, doi: 10.1080/01430750.2017.1298057.

[31] N. Yousefpoor, S. H. Fathi, N. Farokhnia, and H. A. Abyaneh, "THD minimization applied directly on the line-to-line voltage of multilevel inverters," *IEEE Trans. Ind. Electron.*, vol. 59, no. 1, pp. 373–380, 2012, doi: 10.1109/TIE.2011.2143373.

[32] R. E. James Kennedy', "Particle Swarm Optimization," in *Tsinghua Science and Technology*, 1995, pp. 1942–1948, doi: 10.1109/TST.2016.7442504.

[33] R. Poli, J. Kennedy, and T. Blackwell, "Particle swarm optimization: An overview," *Swarm Intell.*, vol. 1, no. 1, pp. 33–57, 2007, doi: 10.1007/s11721-007-0002-0.

Mr. Kaushal Bhatt is M.Tech in power apparatus systems from Nirmatechnical institution, Nirma University, India. He has done his B.Tech from VVP engineering college, Rajkot, India. He has worked with Institute for Plasma Research and Altair engineering Pvt. Ltd. At present, he is operational as an assistant professor in government engineering college, Modasa, Gujarat, India. He has his contribution in fields of power drives for the renewable energy system, multilevel inverters, and advanced electrical machines. He has published articles in refereed national as well as international journals.

Dr. Sandeep Chakravortyis Ph.D. in (Power System), ME Software Engineering from Birla Institute of Technology, Mesra, and Gold Medalist in BE Electrical and Electronics Engineering. He has worked as Dean Academics, Baddi University of Emerging Sciences and Technology, Head of Department of Power System and Coordinator of School of Electronics and Electrical Engineering, Lovely Professional University. He was associated with the Sikkim Manipal Institute of Technology in various designations. He is currently working with Indus University, Ahmedabad, as Dean Academics. He has his contribution in the field of Power System Planning, Multi-Criteria Decision Making Tools, Soft Computing, and have published articles in refereed journals and conferences.