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Selective harmonic elimination in inverters using bio-inspired intelligent algorithms for renewable energy conversion applications: A review

Mudasir Ahmed Memon[a,*], Saad Mekhilef[a,*], Marizan Mubin[a,*], Muhammad Aamir[b]

[a] Power Electronics and Renewable Energy Research Laboratory (PEARL), Department of Electrical Engineering, Faculty of Engineering, University of Malaya, Kuala Lumpur 50603, Malaysia

[b] Department of Electrical Engineering, Bahria University, Islamabad 44000, Pakistan

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ABSTRACT

Observing present scarcity of fossil fuel and emissions of greenhouse gases, electricity generated from Renewable Energy (RE) sources turns out to be the best alternative for generating the power. In RE system, the inverter is normally used to condition the DC power into AC to meet the requirements of load and transmission system. The inverter offers myriad benefits; however, the presence of harmonics (particularly low-order) in the output voltage affects the efficiency and performance of inverter, causes switching losses and decreases the lifetime of the system. In last three decades, significant research has been done to develop the efficient control technique for eliminating the unwanted harmonics. The preliminary review of existing control techniques revealed that the selective harmonic elimination pulse-width modulation (SHEPWM) is more proficient to eliminate the low-order harmonics. However, non-linear transcendental equations used in this technique pose a challenge to solve particularly for calculus-based methods. With the advent of powerful and low-cost computers, bio-inspired intelligent algorithms (BIAs) seem to be a better approach for solving these complex equations. This review paper presents the detailed principle operation of nine well-known BIAs and discusses their application in inverters for harmonic elimination (HE). Moreover, different objective functions are also discussed in this paper which is used by the researchers for HE. Additionally, the performance of five renowned BIAs, namely, Imperialist Competitive Algorithm, Particle Swarm Optimization, Differential Evolution, Bee Algorithm and Genetic Algorithm is critically evaluated. Their performance is analyzed in terms of accuracy, computational complexity, convergence speed, and a number of control parameters. The conclusion has been made on the basis of information extracted from the literature and evaluation results with future recommendations. This single paper covers all the essential information regarding HE in inverters, which will help researchers to design the efficient RE conversion system.

1. Introduction

Fossil fuel-based energy generation industries emit harmful greenhouse gases, such as CO_2 and methane; these gases cause climate change and adds in global warming [1–3]. Anthropogenic climate change can be reduced by generating the electricity using RE sources, such as biomass, the wind, and solar [1]. RE systems are beneficial because they consume nearly zero fossil fuel (e.g., coal, natural gas, and oil), require low maintenance, emit a small percentage of greenhouse gases, and are less costly than conventional energy generation systems in cases where transportation charges of fossil fuels are high [4].

The RE sources like tidal, biomass and solar generate electricity in DC form whereas the load and electrical transmission system utilize AC power. Thus, a converter is needed to convert DC energy into AC form [5,6]. In this situation, inverter converts DC voltages into AC [7–34]. Inverters are used in grid-connected [9,12] or stand-alone [35] RE systems to run a load or any equipment that requires AC power. Inverters are reliable, cost-effective, simple, and efficient devices for energy conversion [36–38]. The inverters are also used in energy transmission, compressors, high-voltage direct current lines, grinding mills and flexible AC transmission systems [39–45]. Due to prevalent applications of inverters in RE system and power electronics based industries, scholars in academia and industries are endlessly concentrating on the research and development of inverters.

In RE systems, Grid-connected solar farms augment the importance of inverters, which employ large-scale photovoltaic (PV) cells [46]. Wind turbines use inverters for the conversion of power [47]. Hybrid RE systems and backup systems also use inverters; in this

* Corresponding authors.
E-mail addresses: memon.mudasir@usindh.edu.pk (M.A. Memon), saad@um.edu.my (S. Mekhilef), marizan@um.edu.my (M. Mubin).

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context, the most popular example is the wind–solar–battery installations in islands and remote areas [35,48,49]. AC appliances, such as motors, lighting systems, and electronic gadgets, are also driven through inverters [35,50,51]. In addition, inverters are used in energy-saving applications in cooling and heating systems. The integration of inverters with variable-speed drive helps in reduction of energy consumption of cooling compressors [50]. Moreover, inverters play an important role in the dynamic stability control and voltage regulation of electrical power systems [48,52]. Due to the widespread usage in RE and power industries, inverter becomes the indispensable part of current and future applications.

Inverters offer numerous advantages; however, their output voltage contains a significant amount of unwanted harmonics, which have negative effects on mechanical and electrical components of the system [53–56]. Among the harmonics, low-order harmonics are more dangerous to systems because they are closer to the fundamental frequency and have significant amplitude. The presence of harmonics in inverters increases switching losses in power switches which degrade the efficiency of RE system and deteriorates overall system performance. For example, it causes speed ripple and torque problem in the induction motor, and it reduces the reliability and lifetime of the system due to the torque pulsation, vibration, and mechanical fatigue. The presence of low-order harmonics in the inverter output voltage also creates undesirable and complicated problems at distribution system when injecting power into the electrical grid [57,58]. For instance, it affects the output power quality of electrical grid; and possibly causes unwanted islanding, voltage fluctuations, and malfunctioning in the protection devices which are connected at the grid side [59]. To overcome these problems, researchers have developed various modulation-based control techniques for eliminating the harmonics which improve performance and efficiency of the inverter [60]. Out of those developed techniques, selective harmonic eliminating pulse-width modulation (SHEPWM) exhibits greater performance because of its superior control over eliminating unwanted low-order harmonics from inverter output voltage [61].

In SHEPWM technique, complex transcendental equations are used to derive optimized firing angles which will force the unwanted harmonics to eliminate from inverter output voltage [62]. However, convergence to an optimum solution is sometimes difficult to achieve due to the involvement of sine and cosine functions which contain different frequencies. Furthermore, this problem becomes more severe in the case of an increase in a number of firing angles and level of the inverter. Despite these complexities, various numerical and algebraic methods like Newton-Raphson (NR) and resultant elimination theory, respectively are proposed to obtain the solution sets for HE. However, the main downside of the earlier technique is, they are based on good initial guesses, thus wrongly chosen guesses result in large iterative cycles and may diverge in extreme cases. The latter technique is computationally very much complex to calculate solutions in real time and their complexity further increases while working on high-level inverters [36–38].

Recently, most of the engineering problems are solved using optimization approach particularly using bio-inspired intelligent algorithms (BIAs) [63–67]. The main strength of these algorithms is, they are not fully dependent on the initial guesses and are also not computationally complex. Furthermore, BIAs are easy to understand and implement using low-cost powerful computers. In RE system, BIAs are applied in many applications [68–84] but their major utilization is HE from the output of the inverters [85–87]. BIAs include the algorithms like Bee Algorithm (BA), Particle Swarm Optimization (PSO), Genetic Algorithm (GA), and Differential Evolution (DE) [64]. The BIAs utilize an objective function that contains non-linear transcendental equations of low-order harmonics and fundamental. This technique minimizes the objective function to get the optimized firing angles which eliminate unwanted harmonics. The performances of BIAs significantly depend upon the formulation of an objective function. The researchers mostly use different objective function in their research to effectively eliminate the unwanted harmonics.

Over the years different BIAs and objective functions have been proposed and published in the literature to solve HE problem of the inverter. However, there is the absence of review article which presents a comprehensive study on this subject. Hence, it is necessary to sum up the efforts exerted to address the HE problem using BIAs and also gather the different objective functions used by the researchers in a single article. The objective of this paper is to explain nine well-known BIAs in detail with full principal operation and their applications in solving HE problem. Additionally, different objective functions used by the researchers for HE are also presented in this paper. Furthermore, the performance of five prominent BIAs is also critically evaluated in terms of accuracy, computational complexity, convergence speed, and a number of control parameters. The selected BIAs are programmed in MATLAB and firing angles are calculated for a 7-level inverter. Based on the information presented in the literature and comparison results, some directions for future research are also given to get more advantages from SHEPWM technique. This single article will be useful for researchers and engineers who are working to improve the efficiency and performance of inverters, particularly in RE systems.

2. Overview of inverters and SHEPWM technique

2.1. Topologies of inverters

Inverters are classified into two categories: 1) current source inverter (CSI) and 2) voltage source inverter (VSI) [45]. RE systems mostly use VSI [12]; therefore, this study is focused on VSI. The VSI is divided into two categories: 1) two-level inverter (generally called as VSI) and 2) multilevel VSI (MVSI) [60]. VSI can generate unipolar or bipolar output voltage waveforms, whereas MVSI generates staircase output voltage waveforms. The latter category provides the output similar to a sinusoidal wave by summing up different DC voltages attached to the input of an inverter. A transformerless structure, low switching losses, high-power quality signals, low electromagnetic interference (EMI), and reduced harmonic distortion are the main advantages of MVSIs [36–38]. The topologies of MVSIs are divided into two types. The first type uses separate DC sources, whereas the second type uses a common DC source for multilevel operation. The cascaded H-bridge (CHB) topology uses separate DC sources, whereas the flying capacitor (FC) topology and the neutral-point-clamped (NPC) or diode-clamped topology use a common DC source for staircase output waveform [39–45]. The structures of these basic topologies are shown in Fig. 1. Various hybrid topologies have also been developed from basic structures, which use less number of components [88–95]. In RE systems, CHB is the most commonly used topology as it has a modular, repetitive, and simple structure. Moreover, this topology also uses less number of components as indicated in Table 1 [7,9,12–34]. This topology is also preferred due to its feature of using separate DC sources for multilevel operations. RE sources, particularly PV cells can be directly connected to the separate cells of CHB, and inverter provides the voltage (sum of all the cells) in staircase output form [12].

2.2. SHEPWM technique

The output voltage quality of an inverter is measured by the total harmonic distortion (THD) factor [51], which is given in Eq. (1):

$$THD = \frac{\sqrt{\sum_{i=2}^{n} V_i^2}}{V_1} \tag{1}$$

where V_i is the voltage of particular harmonics, and V_1 is the fundamental voltage. The efficiency of energy conversion (DC/AC) is also depends on the THD factor [96]. Various organizations have set and

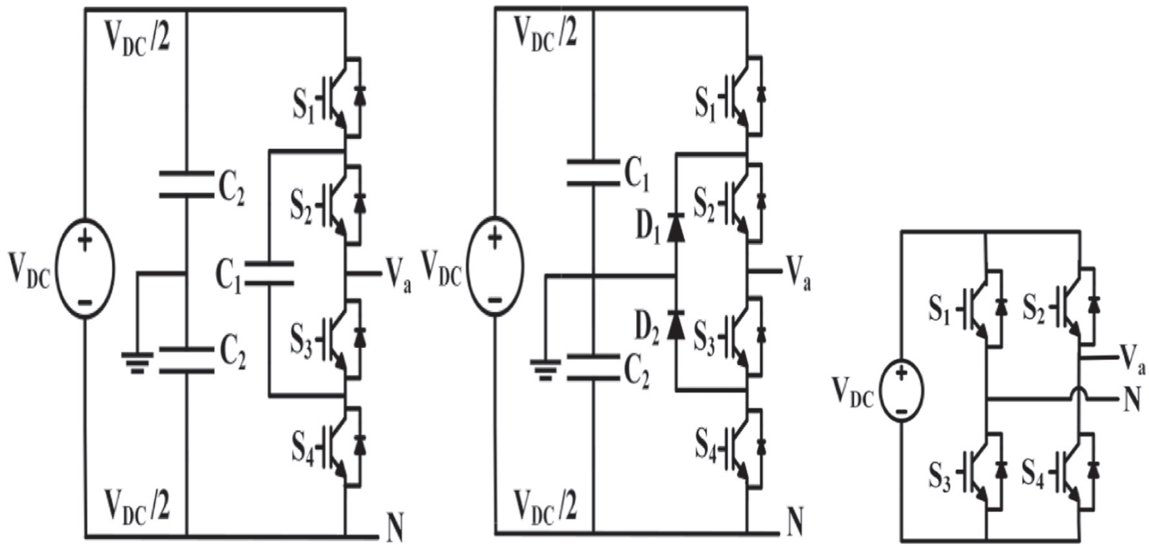


Fig. 1. Topologies of MVSIs.

Table 1
Comparison of basic MVSI topologies.

Topology	Power switches	Clamping diodes	Clamping capacitors	DC bus capacitors
NPC	$2(L-1)$	$(L-1)(L-2)$	0	$L-1$
FC	$2(L-1)$	0	$\frac{(L-1)(L-2)}{2}$	$L-1$
CHB	$2(L-1)$	0	0	$\frac{L-1}{2}$

recommended the limits for THD [97]. To improve the quality of output voltage, different methods have been proposed in literature. They are grouped according to 1) fundamental switching frequency and 2) high switching frequency [36–38]. The main difference between these categories is the number of commutations performed by a power semiconductor during one cycle of fundamental output voltage. In fundamental switching frequency, only one or two commutations performed, whereas in, high switching frequency, multiple commutations are performed in one period of the fundamental output voltage. Optimized harmonic stepped waveform, space vector control, SHEPWM, and optimal minimization of THD are the types of fundamental switching frequency techniques. Sinusoidal pulse-width modulation and space vector modulation are classified as high switching frequency techniques [60,98–102]. The fundamental switching frequency techniques achieve low-cost and highly efficient energy conversion systems. In this technique, SHEPWM exhibits superior performance because of its capability to eliminate unwanted low-order harmonics from inverter output voltage, whereas high-order harmonics can be easily eliminated using passive filters [36–38].

In SHEPWM, the periodic output voltage waveform of MVSI is mathematically expressed using the Fourier series expansion [60] which is given in Eq. (2):

$$f_N(t) = \frac{a_0}{2} + \sum_{n=1}^{N}\left(A_n \cos\left(\frac{2\pi nt}{T}\right) + V_n \sin\left(\frac{2\pi nt}{T}\right)\right) \tag{2}$$

where a_0 is the DC component, A_n denotes even harmonics and V_n represents odd harmonics. The formulation of MVSIs output depends on the shape of the desired output voltage waveform, i.e., single switching per level (type-a) or multiple switching per level (type-b), as shown in Fig. 2.

In type-a output waveform, the maximum fundamental output voltage is achieved with low switching frequency. However, the number

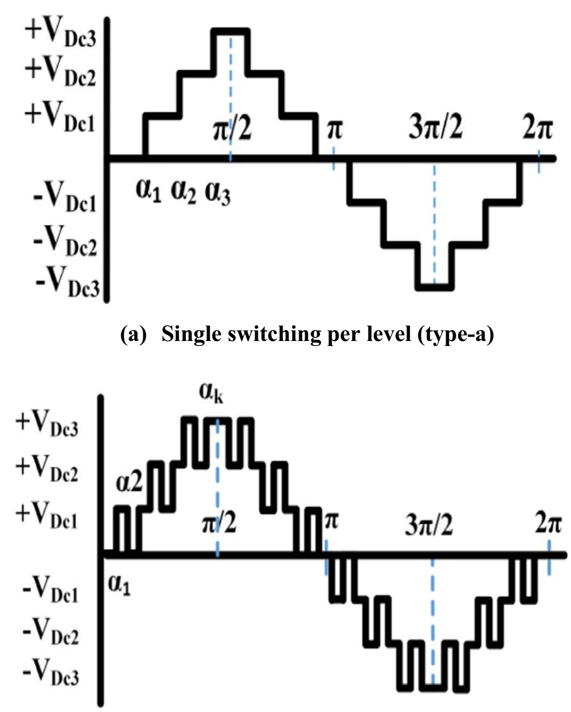


Fig. 2. Staircase output voltage waveform of 7-level inverter.

of unwanted low-order harmonics which are to be eliminated from the MVSI output voltage is limited to $(s-1)$, where s is the number of firing angles or DC sources connected to the input of inverter. To eliminate more number of undesired harmonics, number of levels must be increased. However, this technique increases the complexity and cost of the system. In type-b switching, more number of harmonics are eliminated from the output voltage of MVSIs without increasing the system complexity, number of levels, or inverter cost. However, this technique increases switching losses and produces less fundamental output voltage [60].

The output voltage waveform of MVSI is quarter symmetrical; therefore, all the even harmonics, DC components, and sine terms in the odd harmonics become zero [60]. Hence; for the type-a case, Eq.

(2) is rewritten as Eq. (3):

$$f_N(t) = V_n \sin(n\theta_i) \tag{3}$$

where V_n is the Fourier coefficient, which is expressed in Eq. (4):

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

where V_{DC} is the nominal DC voltage, k_i is the ratio of $(\frac{V_{DC_i}}{V_{DC}})$, and V_{DC_i} is the voltage of DC source i. The equations for the fundamental, 5th & 7th harmonic, and modulation index (M) of the symmetrical 7-level inverter are given in Eq. (5):

$$\left.\begin{aligned} V_1 &= \tfrac{4V_{DC}}{\pi}[\cos(\theta_1) + \cos(\theta_2) + \cos(\theta_3)] \\ V_5 &= \tfrac{4V_{DC}}{5\pi}[\cos(5\theta_1) + \cos(5\theta_2) + \cos(5\theta_3)] \\ V_7 &= \tfrac{4V_{DC}}{7\pi}[\cos(7\theta_1) + \cos(7\theta_2) + \cos(7\theta_3)] \\ M &= \tfrac{\pi V_D}{4SV_{DC}} \end{aligned}\right\} \tag{5}$$

where V_D is the required fundamental voltage. In SHEPWM, the optimized switching angles $(\theta_1, \theta_2, \theta_3)$ of the symmetrical 7-level inverter are derived using Eq. (6):

$$\left.\begin{aligned} M &= \tfrac{1}{3}[cos(\theta_1) + cos(\theta_2) + cos(\theta_3)] \\ cos(5\theta_1) &+ cos(5\theta_2) + cos(5\theta_3) = 0 \\ \cos(7\theta_1) &+ \cos(7\theta_2) + \cos(7\theta_3) = 0 \end{aligned}\right\} \tag{6}$$

The firing angles calculated using Eq. (6) must satisfy the relationship given in Eq. (7):

$$0 < \theta_1 < \theta_2 < \theta_3 < \frac{\pi}{2} \tag{7}$$

For type-b case, the Fourier coefficient of the symmetrical 7-level inverter is given in Eq. (8):

$$\begin{aligned} V_n = \frac{4V_{DC}}{n\pi}\Bigg\{&\left[\sum_{i=1}^{K_1}(-1)^{i-1}\cos(n\theta_i)\right] + \left[\sum_{i=K_1+1}^{K_1+K_2}(-1)^{i-(K_1+1)}\cos(n\theta_i)\right] + \dots \\ &+ \left[\sum_{i=K_1+K_2+1}^{K}(-1)^{i-(K_1+K_2+1)}\cos(n\theta_i)\right]\Bigg\} \end{aligned} \tag{8}$$

Where constant K represents the total number of switching angles; K_1 and K_2 are the number of firing angles in the first and second level of the output voltage waveform, respectively. For example; in 7-level inverter, three transitions per level requires nine firing angles per quarter cycle, as shown in Fig. 2(b). Hence, the Fourier coefficient presented in Eq. (8) is rewritten as Eq. (9) [103]:

$$V_n = \frac{4V_{DC}}{n\pi}(\cos(n\theta_1) \pm \cos(n\theta_2) \pm \dots \pm \cos(n\theta_{T\times s})) \tag{9}$$

where T is the number of firing angles per level. The positive (+) sign in Eq. (9) represents the rising edge, whereas the negative (−) sign represents the falling edge. The firing angles derived from Eq. (9) must satisfy the relationship given in Eq. (10):

$$0<\theta_1 < \theta_2\dots<\theta_{T\times s} < \frac{\pi}{2} \tag{10}$$

In type-b switching, $((T\times s)-1)$ unwanted harmonics can be easily eliminated from the output voltage of the inverter. For example; in 7-level inverter, eight harmonics can be easily controlled and eliminated from the inverter output voltage.

3. Types of SHEPWM technique

In SHEPWM technique, optimized firing angles are calculated from the set of non-linear transcendental equations which eliminate unwanted low-order harmonics from the inverter output voltage. Several SHEPWM techniques have been developed in literature to find the optimized transition points on the time axis which minimize or eliminate the unwanted low-order harmonics. The SHEPWM technique is divided into three major categories: 1) numerical methods (NMs), 2) algebraic methods (AMs), and 3) BIAs [62] (Fig. 3). The overview of each category with their advantages and limitations is presented in the following sections.

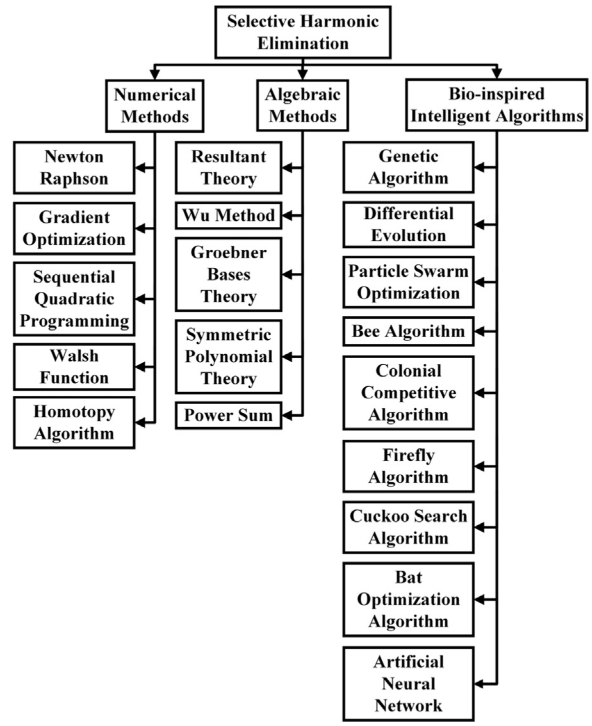


Fig. 3. Types of SHEPWM technique.

3.1. NMs

NMs are fast iterative methods, which calculate optimized solutions within a few iterations. However, these methods are highly dependent on the initial guesses and get stuck at the local minimum solution if appropriate guesses are not provided [36]. Due to its ability to calculate exact and precise solutions, this method is mostly used [104–111]. To guess the initial values for NR, predictive [105] and BIAs techniques have been proposed [104,108]. However, this hybrid technique becomes computationally more complex in the case of guessing the values for high-level inverters, particularly for type-b output voltage waveform. Other improved NMs presented in the literature are Walsh function [112,113], sequential quadratic programming [114], homotopy algorithm [115–118], and gradient optimization [119]. However, the initial guess problem remains unsolved in these methods.

3.2. AMs

In AMs, nonlinear transcendental equations are converted into polynomial equations to get the optimized firing angles. The main advantage of this technique is that all solution are found without using any initial guess [62]. In the literature, Resultant theory [120–122], Wu method [123], Groebner bases theory [62,124], symmetric polynomial theory [125], and power sum [126] methods are applied for HE in inverters. However, these methods are computationally complex and applicable only to low-level inverters. Therefore, these methods are unsuitable to apply on inverters in real-time applications.

3.3. BIAs

The BIAs are the types of artificial intelligence techniques influenced by nature, such as species migration, natural selection, ant colonies, human culture, honey bee colonies, swarms of birds, and schools of fish [63–67]. BIAs are population-based iterative techniques in which initial guesses only have a slight influence on finding optimized solutions. BIAs are easy to understand and simple to program on personal computers using MATLAB or any other computational software. BIAs use an objective function that contains transcendental equations of low-order harmonics and fundamental. This technique minimized the objective function to get the optimized firing angles. The performance of BIAs significantly depends on the formulation of an objective function. Every researcher mostly designs his/her own objective function to satisfy his/her objectives. The most popular BIAs, namely, the Bat Optimization Algorithm (BOA), BA, Cuckoo Search Algorithm (CSA), PSO, Firefly Algorithm (FA), GA, Imperialist Competitive Algorithm (ICA), Artificial Neural Network (ANN) and DE are explained in detail with their HE applications in the following section. Other BIAs have also been reported in the literature, which includes Ant Colony Optimization [127], Clonal Search Algorithm [128], Bacterial Foraging Algorithm [129,130] and Shuffled Frog Leaping Algorithm [131]. However, these algorithms are not frequently applied to solve the HE problem. Also, they have limited features; therefore, they are not included in the detailed explanation.

Apart from all the above-mentioned categories, some totally different approaches like modulation-based harmonic elimination method [132] and four-equation based harmonic elimination method [133–135] are also proposed in the literature to solve the HE problem.

4. Working principles of nine well-known BIAs

4.1. GA

The GA is an adaptive heuristic search technique developed by the students and colleagues of John Holland in the University of Michigan [136]. GA is inspired by the Charles Darwin's theory of "survival of the fittest" and it is shown in Fig. 4. GA is used to solve constrained and unconstrained optimization problems based on natural selection that resembles biological development. GA is started with a set of chromosomes called "population" which contains solutions for the problem. In this algorithm, the fitness of each chromosome is evaluated using the objective function. Healthy parents are selected based on their fitness value using the roulette wheel method, and offspring are produced using the crossover operation for the next generation. The healthy chromosomes in each iteration are likely to be selected as parents to produce offspring. Each offspring has inherited properties from its parents. These properties increased the probability of achieving good solutions in successive iterations. During the mutation stage, a small percentage of the total solutions changed with random solutions, which maintain genetic diversity from one generation to the next. The solution with the best fitness is recorded in each iteration. This procedure continued until the termination criteria is satisfied. GA is less susceptible to getting stuck in local optimum positions than gradient search techniques. However, this algorithm is computationally costly as compared with other techniques.

Genetic Algorithm

```
Objective function f(x).
Initialize parameters CR, MR, and population size nPop.
Generate an initial population of chromosomes.
Evaluate the fitness of each chromosome.
while (t < MaxGeneration) or (!stop criterion)
    Select the best parents for reproduction using the roulette wheel
    method.
    Create offspring through crossover operation between selected
    parents with probability CR.
    Mutate some chromosomes with probability MR.
    Evaluate the fitness of the new chromosomes.
    Find the best chromosome.
end while
```

Fig. 4. Pseudocode of GA.

The GA is first proposed in [137,138] to solve the HE problem in MVSI for the type-a case. The proposed method can eliminate unwanted harmonics from all levels of the inverter without using any extensive analytical expression. In these studies, the objective function given in Eq. (11) is used, and 7- & 11-level inverters are experimentally implemented to validate the algorithm. The proposed algorithm successfully minimized 5th and 7th order harmonics from the output voltage of 7-level inverter, and 5th, 7th, 11th and 13th order harmonics from the 11-level inverter.

$$OF = 100 \times \frac{|V_5| + |V_7| + \ldots + |V_n|}{|V_1|} \tag{11}$$

Where n is the order of harmonic and its formulation depends upon the number of firing angles s. If the number of firing angles is even, then s will be $(3s-1)$; if it is odd, then s will be $(3s-2)$. In [139], GA is applied to improve the power factor of the unipolar output voltage of a single-phase inverter. The starting three harmonics, namely, 3rd, 5th, and 7th, are addressed and eliminated from the inverter output voltage using the objective function given in Eq. (12). In this study, the performance of proposed algorithm is found superior in most of the cases than NR in terms of faster convergences, less computational burden and achieving guaranteed global minima.

$$OF = \frac{10}{|V_3| + |V_5| + |V_7|} \tag{12}$$

In [140], the authors proposed a hybrid real coded GA (RCGA) algorithm to eliminate unwanted harmonics in MVSI for equal and non-equal DC sources. This technique replaced binary genes with real coded values. The first phase of the proposed algorithm utilized RCGA, which performed global searching and found good initial guesses. The second phase utilized the direct search optimization method which performed the local refinement around the solutions. This method improved the accuracy of the solution and reduced the convergence time. In this algorithm, firing angles are calculated for type-b output waveform using the objective function given in Eq. (13) and experimentally this method is tested on a 5-level inverter for validation.

$$OF = (V_1 - V_D)^2 + V_3^2 + V_5^2 + \ldots + V_n^2 \tag{13}$$

In [141], the same approach presented in [140] is validated on a single-phase inverter using weighted THD (WTHD) as an objective function which is given in Eq. (14):

$$WTHD = \frac{\sqrt{\sum_{n=2}^{\infty} (w_n V_n)^2}}{V_1} \tag{14}$$

The term w_n is the weighting factor, selected between 0 and 1. Several studies have defined w_n as $(\frac{1}{n})$, where n represent the harmonic order. In [108], PSO and RCGA are individually applied to calculate the firing angles for type-a output voltage waveform to eliminate the unwanted harmonics. The objective function given in Eq. (15) is used to derive firing angles for 7-level diode clamped inverter. For improving the accuracy, the solutions obtained from PSO and RCGA are further inputted into NR which gives precised and exact solutions.

$$OF = w_1|3M - V_1| + w_2|V_5| + w_3|V_7| \tag{15}$$

In [142], GA is applied to solve the HE problem of a new family of MVSIs, which contained a reduced number of power switches. In this study, 5- and 7-level inverters are designed with six and eight power switches, respectively. Moreover, the proposed configuration can be easily extended to design any MVSI level. The algorithm is proposed for type-a output waveform, which generates multiple solutions for each M. The solutions that provided minimum THD are selected in the end. This algorithm is experimentally validated on 5- and 7-level inverters. In [143], GA is proposed to eliminate the unwanted harmonics from MVSI output voltage which have fewer power switches using the objective function given in Eq. (1). However, the algorithm is tested only through simulations. In [144], GA and evolutionary programming (EP) are individually applied to improve the performance of an induction motor drive by eliminating specific low-order harmonics without using a dual transformer. These algorithms individually calculated the firing angles of a three-phase inverter for unipolar output using the objective function given in Eq. (16). In this research, elitism strategy is used which saved the best chromosome obtained in the current iteration and copied it to the next iteration. The elite method helped when a probability of losing good solutions in a crossover or mutation operation exists. In this study, harmonics up to the 19th order are eliminated using evolutionary algorithms. In this research, the THD of the output voltage is greatly reduced using GA approach.

$$OF = \frac{1}{1 + [(V_1 - M)^2 + V_5{}^2 + \ldots + V_{19}{}^2]} \tag{16}$$

In [145], improved objective function-based GA is proposed for type-a output waveform. The proposed GA efficiently eliminated unwanted low-order harmonics from the output voltage of MVSI. The objective function used in this study is given in Eq. (17). This method is verified through simulations on a 9-level inverter.

$$OF = \left[\left|100\frac{V_D - V_1}{V_D}\right|^4 + \sum_{s=2}^{S}\frac{1}{h_s}\left|50\frac{V_{h_s}}{V_1}\right|^2\right] \tag{17}$$

Where h_s is the order of particular harmonic (e.g., $h_2 = 5$ and $h_3 = 7$). The first part of the objective function is fined with a power of 4, thereby keeping the error between V_1 and V_D under 1%. This power has negligible effect for violations that are under 1% error. The second part of the equation is fined with a power of 2, which limited the unwanted low-harmonics under 2% of the fundamental. It is further divided by its harmonic order, which increased the weight of eliminations for the considered harmonic. In [146], the method presented in [140] is applied to a 3-Level Active NPC converter to eliminate neutral point current. Ideally, the inverter output waveform has zero neutral point current due to its half and quarter symmetrical shape. However, a small amount of neutral point current circulates due to the variation in the operating conditions and load, which decreases the performance and efficiency of the system. To handle this issue; the proposed algorithm is designed to work in two steps; in the first step, firing angles are calculated using ordinary SHEPWM equations which eliminate specific harmonics, and in second step, the calculated switching angles are slightly modify to minimized the neutral point current. This minor modification is calculated according to discharging and charging timings of the input capacitors.

In [147], a modified version of [145] is applied to and validated on a 30-k VA scaled-down 7-level inverter. In this research, the program run until the objective function value reached to or below 10^{-2} for each M or iterations reached to the maximum number. In [148], the modified GA is applied to eliminate harmonics from the 5-level inverter using the objective function given in (17). In addition, the strategy is proposed for sharing the desired power among the cells of 5-level inverter. In [149], GA is applied to eliminate the 3rd and 5th harmonics from the multifunctional 7-level inverter using the objective function given in (17). The designed inverter operated in two modes; in one mode it worked as a battery charger, and in the second mode it worked as an inverter which made the proposed system suitable for standalone applications such as PV systems. For convenience, a summary of GA for HE applications is provided in Table 2.

4.2. DE algorithm

DE is first developed by Storn and Price [150] (Fig. 5). This is a population-based global optimization algorithm that iteratively found the optimum solution for complex problems. The fitness value of each agent in this algorithm is evaluated using an objective function. Then, in each iteration and for each population member, three individuals, (e.g., A, B, and C) are randomly selected from the population and noisy random (mutant) vector Y is formed as given in Eq. (18):

$$Y = A + F(B - C) \tag{18}$$

where F is the mutation factor selected between [0, 2]. The crossover operation between noisy random vector Y and target vector x_i produced an offspring vector Z. Trial vector T is then created based on the probability of the crossover rate CR as given in Eq. (19):

$$T = \begin{cases} Z & if\ rand \le CR \\ x_i & if\ rand > CR \end{cases} \tag{19}$$

The value of CR is selected between [0, 1]. If the fitness value of trial vector T is less than the fitness value of target vector x_i, then trial vector T replaced target vector x_i as given in Eq. (20):

$$x_i = \begin{cases} T & if\ f(T) \le f(x_i) \\ x_i & if\ f(T) \ge f(x_i) \end{cases} \tag{20}$$

This procedure continued for each member of the population. The program is terminated when iterations reached to the maximum number or when objective function value reached to the desired level. Numerous formulations are used to generate noisy or mutant vectors; these formulations are explained in detail in [151].

The DE is first proposed in [152,153] to eliminate unwanted harmonics from the bipolar output voltage of a three-phase inverter. In this research, DE is found simple and has high convergence speed compared to GA. Also, it consumes much shorter time for calculation of optimum firing angles. In this algorithm, $(DE/best/1/bin)$ mutation scheme is used, and the objective function given in Eq. (21) is adopted to derive firing angles.

$$OF = (V_1 - M)^2 + V_5^2 + \ldots + V_n^2 \tag{21}$$

In [154], an enhanced version of DE is applied to eliminate the inverter harmonics, which improved the performance of an induction motor. In this research, $(DE/current\ to\ best/1)$ mutation scheme is used and objective function given in Eq. (22) is considered to derive the firing angles.

$$OF = ||V_1| - |M|| + |V_5| + |V_5| + \ldots + |V_n| \tag{22}$$

In [155], DE is applied to an asymmetrical 7-level inverter to eliminate 3rd and 5th harmonics from the output voltage. The firing angles are calculated using the objective function given in Eq. (23) with $(DE/rand/1)$ mutation scheme.

$$OF = (V_1 - M)^2 + V_3^2 + V_5^2 \tag{23}$$

In [156], DE is applied to find the firing angles for type-b output waveform, thereby eliminating the unwanted harmonics by using the objective function given in Eq. (24). This algorithm is tested only through simulations on a 5-level inverter. In [157], DE is adopted to solve the HE problem in a 15-level inverter for type-a output waveform using the objective function given in Eq. (24). In the proposed method, the fundamental voltage is precisely controlled over a wide range of M by maintaining a very low THD. The trajectories of switching angles are also continuous over the whole range of M which makes it suitable for variable speed drive and utility applications. This research used Eq. (24) as an objective function and $(DE/rand/1)$ mutation scheme for HE.

$$OF = |V_1 - M| + |V_5| + |V_7| + \ldots + |V_n| \tag{24}$$

Table 2
The use of GA for HE applications (Summary).

Refs.	Objective of the study	Remarks
[137,138]	To eliminate specific harmonics in MVSI (type-a)	GA is applied to eliminate specific harmonics using the objective function given in Eq. (11).
[139]	To improve the power factor of a single-phase inverter (type-b)	GA is applied to eliminate the starting three harmonics (third, fifth, and seventh) from the output voltage of a single-phase inverter using the objective function given in Eq. (12).
[140]	To eliminate selected harmonics from the output voltage of equal/unequal MVSI (type-b)	A hybrid algorithm (RCGA + DS) is applied to eliminate the unwanted harmonics in MVSI using the objective function given in Eq. (13).
[141]	To eliminate specific harmonics in VSI (type-b)	The same method applied in [140] is used to eliminate the unwanted harmonics in VSI using the objective function given in Eq. (14).
[108]	To eliminate selected low-order harmonics in an NPC-MVSI converter (type-a)	RCGA and PSO individually calculated the firing angles (solutions), which are further inputted into NR for local refinement. The objective function used in this work is given in Eq. (15).
[142]	To eliminate selected harmonics from the output voltage of a newly introduced family of MVSIs (type-a)	GA is applied to eliminate the harmonics from the output voltage of MVSIs, which contains less number of switches.
[143]	To eliminate the unwanted harmonics in MVSI that contains a reduced number of power switches (type-a)	GA is used to find the firing angles using Eq. (1). The firing angles eliminate the unwanted low-order harmonics from the output voltage of the reduced number of power switch-based MVSI.
[144]	To improve the efficiency of an induction motor drive system (type-b)	GA and EP separately calculated the firing angles using the objective function given in Eq. (16). The unwanted harmonics (i.e., 5th, 7th, 11th, 13th, 17th and 19th) are eliminated from the output voltage of the inverter.
[145]	To efficiently eliminate low-order harmonics from the output voltage of MVSI (type-a).	GA based on the improved objective function given in Eq. (17) is applied to efficiently eliminate the unwanted low-order harmonics from the output voltage of MVSI.
[146]	To eliminate the neutral point current in a three-level active NPC converter	The method proposed in [140] is applied to eliminate the neutral point current from a three-level active NPC converter.
[147]	To improve HE performance in MVSI (type-a)	The method proposed in [145] is modified, which efficiently eliminated the selected harmonics from MVSI.
[148]	To eliminate unwanted harmonics in inverter and make a strategy for desired power sharing among cells.	The modified GA is proposed based on the objective function given in Eq. (17) to eliminate unwanted harmonics from the 5-level inverter. Furthermore, the strategy for desired power sharing among cells is also proposed.
[149]	To eliminate unwanted low-order harmonics from multifunctional inverter	The improved GA based on the objective function given in Eq. (17) is proposed to eliminate 3rd and 5th harmonics from the multifunctional 7-level inverter.

Differential Evolution Algorithm

```
1. Objective function f(x).
2. Initialize parameters CR, F, and population size nPop.
3. Generate an initial population of agents.
4. Evaluate the fitness of each agent.
5. while (t < MaxGeneration) or (!stop criterion)
6.      for i = 1: nPop
7.          Randomly select three agents, e.g., A, B, and C, from the
            population and generate noisy vector Y.
8.          Create offspring vector Z via crossover operation between target
            vector x_i and noisy vector Y.
9.          Create trail vector T using vector Z or target vector x_i based on
            the probability of CR.
10.         Evaluate the fitness of the trial vector.
11.         If f(T) < f(x_i),
12.           Then replace agent x_i with trial vector T.
13.         end if
14.     end for i
15.     Find the best agent.
16.end while
```

Fig. 5. Pseudocode of the DE algorithm.

Particle Swarm Optimization

```
1. Objective function f(x).
2. Initialize parameters c_1, c_2, w_max, w_min, and population size nPop.
3. Generate an initial population of particles.
4. Evaluate the fitness of each particle and set all initial positions as P_Best_xi.
5. while (t < MaxGeneration) or (!stop criterion)
6.      Select the G_Best particle in the swarm, which has the minimum
        fitness value.
7.      for i = 1: nPop
8.          Calculate the velocity of particle x_i.
9.          Update the position of particle x_i.
10.     end for i
11.     for i = 1: nPop
12.         Evaluate the fitness of updated particle x_i.
13.         if f(x_i) < f( P_Best_xi),
14.           Then set current position as P_Best_xi.
15.         end if
16.     end for i
17.     Find the best particle.
18.end while
```

Fig. 6. Pseudocode of the PSO algorithm.

4.3. PSO algorithm

The PSO algorithm is first developed by Eberhart and Kennedy [158] (Fig. 6). The PSO algorithm is a population-based iterative method inspired by the sociological behavior of swarming birds and schooling fish as they search for food or any target. The algorithm is started with a random population called particles, which have solutions for a problem. The initial position of each particle is considered as its personal best $P_{Best_{x_i}}$. The fitness of each particle is evaluated using an objective function, and the global best particle G_{Best} is selected among the swarm based on the minimum fitness value. The movement of a particle is influenced by three forces: 1) inertia, 2) personal best experience $P_{Best_{x_i}}$, and 3) the experience of the global best particle G_{Best}. The particles in the swarm updated their velocity using Eq. (25) and position using Eq. (26):

$$v_{ij}^{t+1} = (v_{ij}^{t} \times w^{t+1}) + [c_1 \times r_{1j}^{t} \times ({P_{Best}}_{xi,j}^{\,t} - x_{ij}^{t})] + [c_2 \times r_{2j}^{t} \times (G_{Best} - x_{ij}^{t})] \tag{25}$$

$$x_{ij}^{t+1} = x_{ij}^{t} + v_{ij}^{t+1} \tag{26}$$

where w^{t+1} is the inertia weight which is calculated using Eq. (27):

$$w^{t+1} = w_{max} - \left(\frac{w_{max} - w_{min}}{TNI} \times CI\right) \tag{27}$$

where CI is the current iteration, and TNI is the total number of iterations. The constants c_1 and c_2 are the acceleration coefficients which are selected between [0, 2]. They controlled the influence of social experience and personal experience, respectively. The r_{1j}^{t} and r_{2j}^{t} are the uniformly distributed random numbers generated between [0, 1]. The w_{min} and w_{max} are the minimum and maximum values of inertia weight, respectively. If any particle founds a better position compared to its recorded personal best after updating the position and velocity, then the particle will memorize the current position as $P_{Best_{xi}}$. The updating procedure of particles is ended when the cycles reached to the maximum number or any other stopping criteria is satisfied.

In [108], a hybrid PSO algorithm is proposed to solve the HE problem in a 7-level diode clamped inverter for type-a output waveform using the objective function given in Eq. (15). The PSO is first proposed in this technique to provide good initial guesses to NR. In [159], PSO is applied to minimize the unwanted harmonics (i.e., 5th, 7th, 11th, and 13th) in the output voltage of VSI for unipolar and bipolar waveforms. In this study, the researchers used the THD formula given in Eq. (1) as an objective function to control and minimize the output voltage THD. In this research, PSO algorithm is found effective, simple to implement and inexpensive in terms of time required and memory. In [160], the same approach presented in [159] is adopted to find the firing angles, which minimized the output voltage THD of the 7-level inverter for type-b switching. In [161], the unwanted harmonics in PV-connected inverters are minimized using the same approach proposed in [159]. In [162], PSO using the objective function given in Eq. (28) is proposed to eliminate specific harmonics from the output voltage of the asymmetrical inverter and firing angles are calculated for type-a output waveform. The overall proposed system is suitable for UPS systems, large variable speed drives, and online utility applications such as static var compensation. This algorithm is experimentally validated on 7- and 9-level inverters.

$$OF = \left[\sum_{i=1}^{s} k_1 \cos(\theta_i) - M\right]^2 + \left[\sum_{i=1}^{s} k_2 \cos(3\theta_i)\right]^2 + \ldots + \left[\sum_{i=1}^{s} k_s \cos((2s-1)\theta_i)\right]^2 \tag{28}$$

In [163], an improved version of PSO is proposed to eliminate the unwanted harmonics from type-a output waveform using the objective function given in Eq. (29). This algorithm is validated only through simulation on 7- and 11-level diode clamped inverters.

$$OF = w_1\left|V_1 - \frac{n-1}{2}M\right| + \sum_{j=2}^{\frac{n-1}{2}} w_j|V_j| \tag{29}$$

As harmonic minimization in MVSI involves complex nonlinear transcendental equations having multiple local minima which result in a non-optimum solution. To address this issue, PSO based on the species seed technique is proposed in [103]. In this research, firing angles are computed for type-b output waveform, and harmonics up to the 50th order are minimized using the objective function given in Eq. (30). This algorithm is experimentally validated on the 11-level inverter.

$$OF = 100 \times \left|M - \frac{|V_1|}{sV_{DC}}\right| + \frac{|V_5| + |V_7| + \ldots + |V_{49}|}{sV_{DC}} \tag{30}$$

In [164], PSO based simple approach is proposed to eliminate the unwanted harmonics from unequal DC source inverter using the objective function given in Eq. (30). The main benefit of using this approach is, it easily calculates solutions for a high number of levels which is not possible using resultant theory or iterative methods. In this research, firing angles are calculated for type-a output waveform, and the algorithm is validated on an 11-level inverter. In [104], a hybrid PSO algorithm is proposed to eliminate the unwanted low-order harmonics in modular MVSI. In this algorithm, PSO is used for finding the global best solution which is further refined by NR for improving the accuracy and precision in the solution. The proposed algorithm calculated firing angles for type-a output waveform using the objective function given in Eq. (31). This algorithm is experimentally validated on a 5-level inverter.

$$OF = \left|\sum_{k=1}^{s} cos(\theta_k) - \frac{\pi M}{2}\right| + \sum_{l=5,7,11,..}^{2s-1} \left|\sum_{k=1}^{s} \cos(l\theta_k)\right| \tag{31}$$

In [165], the approach presented in [163] is adopted for type-a output waveform but applied as a minimization technique. In this study, the initial six harmonics, namely, the 3rd, 5th, 7th, 9th, 11th, and 13th orders, are addressed and minimized, thereby reducing THD of the output voltage. This algorithm is validated on a three-phase 5-level inverter. In [166], the memetic algorithm (MA) is proposed to minimize the unwanted low-order harmonics from the type-a output waveform using the objective function given in Eq. (32). In each iteration, proposed algorithm is divided into two stages. In the first stage, PSO is applied on each member of the population and calculated optimized solutions. In the second stage, the few particles based on the minimum objective function value are selected and handed over to mesh adaptive direct search algorithm (MADS) for local refinement to increased the convergence speed and quality of solutions. For validation, this algorithm is experimentally applied on the 7-level inverter for minimizing the 5th, 7th, 11th and 13th order harmonics.

$$OF = |3.82M - V_1|^4 + |V_5|^2 + |V_7|^2 + |V_{11}|^2 + |V_{13}|^2 \tag{32}$$

In [167], the same approach proposed in [166] is applied to eliminate the 5th and 7th order harmonics from the output voltage of 7-level inverter using the objective function given in Eq. (33).

$$OF = |3.82M - V_1|^4 + |V_5|^2 + |V_7|^2 \tag{33}$$

In [37], an improved version of the approach proposed in [166] is applied to and validated on a 7-level inverter using the objective function given in Eq. (17). The proposed algorithm generated high-quality solutions within a few iterations. In 48% of the M range, MA minimized the fitness value to less than 10^{-30}. In [168], PSO is proposed to eliminate the harmonics from stand-alone PV inverter. The proposed method is applied for finding the switching patterns of unipolar and bipolar output wave. In this algorithm, harmonics up to 15th order are eliminated from the inverter output voltage using the objective function given in (34). The summary of the PSO for HE application is provided in Table 3.

$$OF = \left\{\frac{16}{\pi^2}\left[\left(1 + \sum_{i=1}^{K}(-1)^i\cos(\theta_i)\right) - M\right]^2 + \left[\frac{4}{n\pi}\left(1 + \sum_{i=1}^{K}(-1)^i\cos(n\theta_i)\right)\right]^2\right\} \tag{34}$$

4.4. BA

BA algorithm is first developed by Karaboga and Yang [169] (Fig. 7). This algorithm is basically inspired by the foraging behavior of honey bees. Principally, this algorithm is divided into three phases: 1) employed or forager bee phase, 2) onlooker or observer bee phase, and 3) scout bee phase. In this algorithm, the fitness of each food source is calculated using an objective function. In each iteration, employed bees searched new food sources v_{ij} in the neighborhood of x_{ij} using Eq. (35) and updated the food sources if they found improved nectar.

$$v_{ij} = x_{ij} + \Phi(x_{ij} - x_{kj}) \therefore k\ isthe\ random\ index \tag{35}$$

Where Φ is the random number generated between [− 1, 1]. After the completion of employed bee phase, the best information about food sources is passed on to onlooker bees. In the onlooker bee phase, bees are maximally sent to the locations where employed bees have found a large amount of nectar. Onlooker bees searched for new food sources v_i around x_i. If the found sources have a better nectar supply than the current food sources, then these current food sources will be replaced with the new ones. In each iteration, the bees from both phases collaborated with each other which resulted in improved solutions. If some food sources are not improved for a certain number of trials, then

Table 3
The use of PSO for HE applications (Summary).

Ref.	Objective of the study	Remarks
[159]	To control THD and remove discontinuities in the HE solution for VSI (type-b)	PSO used the THD formula as an objective function to control and minimize the THD of VSI. This method also removed the discontinuities in a solution.
[160]	To minimize THD and remove discontinuities in the HE solution for MVSI (type-b)	This work is another application of the method proposed in [159] for MVSI.
[161]	To minimize the output voltage THD in PV-connected inverter (type-a)	The approach proposed in [159] is applied to minimize the THD in the PV-connected inverter.
[162]	To eliminate selective harmonics in asymmetrical MVSI (type-a)	PSO is applied to eliminate the unwanted low-order harmonics from the output of asymmetrical MVSI using the objective function given in Eq. (28).
[163]	To eliminate the unwanted harmonics from the output voltage of diode-clamped MVSI (type-a)	PSO based on the improved objective function given in Eq. (29) is applied to eliminate the unwanted low-order harmonics from the output voltage of diode-clamped MVSI.
[103]	To minimize THD with improved harmonic control in MVSI (type-b)	Modified PSO based on the species technique is proposed and applied to minimize the harmonics up to the 50th order in an 11-level inverter using the objective function given in Eq. (30).
[164]	To eliminate selective harmonics from unequal MVSI (type-a)	PSO is applied to eliminate the low-order harmonics in unequal MVSI using the objective function given in Eq. (30).
[104]	To efficiently eliminate the unwanted harmonics in modular MVSI (type-a)	A hybrid PSO algorithm (PSO-NR) is applied to precisely eliminate the unwanted low-order harmonics from the output voltage of modular MVSI using the objective function given in Eq. (31).
[165]	To minimize the selective harmonics in an MVSI inverter	PSO is applied to minimize the unwanted harmonics in MVSI using the objective function given in Eq. (29).
[166]	To minimize the unwanted harmonics by using the improved control in MVSI (type-a)	MA is applied to minimize the unwanted harmonics from the output voltage of adjustable DC source MVSI using the objective function given in Eq. (32).
[167]	To efficiently eliminate the unwanted harmonics in MVSI (type-a)	This work is an extension of [166] to eliminate the harmonics in MVSI using the objective function given in Eq. (33).
[37]	To efficiently eliminate the selected harmonics in MVSI (type-a)	This work used the same method proposed in [166] with improved control to eliminate the unwanted harmonics. This work used Eq. (17) as an objective function.
[168]	To efficiently eliminates the harmonics from stand-alone PV inverter (type-b).	The PSO is applied to eliminate the unwanted harmonics from stand-alone PV inverter using the objective function given in (34).

Bee Algorithm

1. *Objective function $f(x)$.*
2. *Initialize parameter L and population size $nPop$.*
3. *Generate an initial population of food sources.*
4. *Evaluate the fitness of each food source.*
5. **while** $(t < MaxGeneration)$ or (!stop criterion)
6. **for** $i = 1{:}nPop$ % employed bee phase
7. *Generate new solution $v_{i,j}$ in the neighborhood of $x_{i,j}$.*
8. **If** $f(v_{i,j}) < f(x_{i,j})$,
9. *Then replace $x_{i,j}$ with the new food source $v_{i,j}$.*
10. ***end if***
11. **end for *i***
12. *Select the best food sources using the roulette wheel method.*
13. **for** $i = 1{:}nPop$ % onlooker bee phase
14. *Generate new solution v_i from solution x_i.*
15. **if** $f(v_i) < f(x_i)$,
16. *Then replace x_i with the new food source v_i.*
17. ***end if***
18. **end for *i***
19. *If any food source does not improve* % scout bee phase *for a L number of trials, then change it with the new food source.*
20. *Save the best food source.*
21. **end while**

Fig. 7. Pseudocode of BA.

scout bees will be sent to change the food sources randomly. This procedure continued until the termination criterion is satisfied.

The BA is first proposed in [38] to eliminate the unwanted harmonics from type-a output waveform in the 7-level inverter using the objective function given in Eq. (17). In this study, the performance of BA is found superior to GA and results showed that the proposed algorithm minimized 48% of the M range below the objective function value 10^{-7}.

Imperialist Colony Algorithm

1. *Objective function $f(x)$.*
2. *Initialize parameters, β, ξ, and population size $nPop$.*
3. *Generate an initial population of countries.*
4. *Evaluate the fitness of each country.*
5. *Create n empires and assign one imperialist imp_n to each empire based on the minimum fitness value.*
6. *Assign the remaining countries N_{col} as colonies to the empires. The empire with the maximum power P_n holds the maximum number of colonies $N.C_n$.*
7. **while** $(t < MaxGeneration)$ or (!stop criterion)
8. **for** $i = 1{:}n$
9. *Move $colonies_i$ of empire i toward their imperialist imp_i.*
10. **end for *i***
11. **for** $i = 1{:}n$
12. *Evaluate the fitness of each $colony_i$ in Empire i.*
13. **if** $f(colony_i) < f(imp_i)$,
14. *Then exchange their positions.*
15. ***end if***
16. **end for *i***
17. **if** $n > 1$,
18. *Then compute the total cost $T.C._n$ of empires.*
19. *Pick the weakest colony from the weakest empire and give it to the empire that has the most likelihood to possess it.*
20. **for** $i = 1{:}n$
21. **If** number of $colonies_i$ *in empire i =0,*
22. *Then eliminate empire i*
23. $n = n - 1$.
24. **end if**
25. **end for *i***
26. **end if**
27. *Save the best Imperialist.*
28. **end while**

Fig. 8. Pseudocode of ICA.

4.5. ICA

ICA is first developed by Atashpaz-Gargari and Lucas [170] (Fig. 8). This algorithm is Inspired by imperialistic competition. The population in ICA is called "countries" which are divided among several empires. Each empire is comprised of one imperialist and several colonies. All empires in the world competed with each other, and strong empires tried to overtake the colonies of weak empires. The loss of colonies weakened the power of an empire, causing it to collapse eventually. Finally, only one empire with one imperialist remained in the world who ruled over all the colonies. In this algorithm, the fitness value of all the countries is evaluated using an objective function. After finding the fitness, countries are sorted in ascending order and starting n countries are selected as an imperialist imp_n. To divide the number of colonies, the normalized cost C_n and power P_n of each imperialist is first calculated using Eqs. (36) and (37), respectively:

$$C_n = c_n - max\{c_i\} \tag{36}$$

$$P_n = \left| \frac{C_n}{\sum_{i=1}^{n} C_i} \right| \tag{37}$$

Then, based on the normalized power of each imperialist, colonies are divided using Eq. (38):

$$N.\ C_n = round\{P_n \times N_{col}\} \tag{38}$$

In each iteration, the colonies in an empire moved towards their relevant imperialist using Eq. (39):

$$x_{new} = x_{old} + \beta \times rand \times [x_{imp} - x_{old}] \tag{39}$$

where β is the constant number that must be selected greater than 1, and $rand$ is the uniformly distributed random number generated between [0, 1]. After updating the colonies, if fitness value of any colony is found less than its imperialist fitness, then their positions will be exchanged. The total power of an empire is calculated using Eq. (40):

$$T.\ C_n = Cost\,(imp_n) + \xi mean\,\{cost\,(colonies_n)\} \tag{40}$$

where ξ is the positive number that must be less than 1, and $colonies_n$ denotes the colonies of empire n. To ensure the fair competition, the normalized total cost of each empire is calculated using Eq. (41).

$$N.\ T.\ C_n = T.\ C_n - max\{T.\ C_i\} \tag{41}$$

Where $T.\ C_n$ is the total cost of nth empire. Then; based on the normalized cost, the possession probability of each empire is calculated using Eq. (42)

$$P_{P_n} = \left| \frac{N.\ T.\ C_n}{\sum_{i=1}^{n} N.\ T.\ C_i} \right| \tag{42}$$

To hand over the weak colony, the possession probability of each empire is arranged in a vector form as given in Eq. (43):

$$P = [P_{P_1}, P_{P_2}, P_{P_3} \ldots P_{P_n}] \tag{43}$$

Then, vector R is created which has the same dimensions as P, which contains uniformly distributed random numbers between [0, 1], as given in Eq. (44).

$$R = [r_1, r_2, r_3, .. r_n] \tag{44}$$

After that, vector D is formed by simply subtracting R from P as given in Eq. (45).

$$D = P - R \tag{45}$$

The weak colony will be handed over to the empire whose relevant index in D has the maximum value.

This competition procedure continued in each iteration, which resulted in the collapse of a weak empire and its colonies are captured by strong empires. Empires with zero colonies are eliminated from the competition. In the end, only one empire, which covered all the colonies in the world, is remained. The imperialist of a powerful empire and its colonies hold the same value of the objective function that means, there is no any difference between them. The program will be terminated when all the empires, except the most powerful one, have collapsed, and all the colonies have been captured by the most powerful empire, or if the iterations reached to the maximum number.

The ICA is first proposed in [171] to eliminates the harmonics from MVSI using the objective function given in Eq. (17). However, this algorithm is only tested through simulation. A 13-level inverter is designed, and firing angles are derived for type-a output waveform that eliminated the 5th, 7th, 11th, 13th, and 17th order harmonics from the output voltage of the inverter. On comparison with continuous GA (CGA) and PSO algorithm, the probability of finding global minima of ICA is found higher. Also, the computational cost of ICA is found less than CGA and PSO algorithm due to its less number of referrals to the objective function in each iteration.

In [172], the approach proposed in [171] is adopted along with a DC–DC converter. The converter improved the performance of the proposed method in situations where the conventional method did not provide solutions. The algorithm is validated experimentally on a 9-level inverter, and firing angles are derived for type-b output waveform. In [36], an improved version of the approach proposed in [171] is implemented for equal and non-equal DC sources and validated on a 7-level inverter. In [173], ICA is proposed to mitigate the low-order harmonics from the output voltage of cascaded transformer inverter which contains reduced number of component. The objective function given in (30) is used to drive the optimum switching angles and this algorithm is experimentally validated on the single phase 9-level inverter.

4.6. FA

FA is first proposed by Yang [174] (Fig. 9). This algorithm is inspired by the flashing behavior of fireflies. FA is flexible, simple, and easy to implement. In FA, the light intensity of all fireflies is calculated using an objective function. On the basis of the intensity value, less bright fireflies moved toward the brighter fireflies in the swarm and their attractiveness is inversely proportional to their distance. Less bright firefly x_i moved toward brighter firefly x_j using Eq. (46):

$$x_i^{t+1} = x_i^t + \beta_o e^{-\gamma r_{ij}^m}\left(x_j^t - x_i^t\right) + \alpha\left(rand - \frac{1}{2}\right),\ m \geq 1 \tag{46}$$

where x_i^t is the current position of a firefly, r is the Cartesian distance between two fireflies, β_o is the attractiveness at distance $r = 0$, α is the randomization parameter that controlled the exploration and exploitation of search space, and γ is the light absorption coefficient that determines the convergence speed and behavior of FA.

The FA is first proposed in [175] to find the firing angles of type-a output waveform for an 11-level inverter using the objective function given in Eq. (30). The 5th, 7th, 11th, and 13th order harmonics are addressed and eliminated from inverter output voltage. In [176], improved FA is applied to eliminate the unwanted harmonics from the output voltage of asymmetrical 11-level inverter using the objective function given in Eq. (47). The performance of proposed algorithm is found better than PSO and BA in terms of achieving less output voltage THD and consuming a smaller amount of time in finding the optimized

Firefly Algorithm

```
Objective function f(x).
Initialize parameter γ and population size nPop.
Generate the initial population of fireflies.
Evaluate the light intensity I_i of all the fireflies.
while (t < MaxGeneration) or (!stop criterion)
    for i = 1:nPop
        for j = 1:nPop
            if (I_j < I_i),
                Then move firefly x_i toward x_j.
            end if
            Vary attractiveness with distance r via exp^(−γr).
            Evaluate new solutions and update light intensity.
        end for j
    end for i
    Rank the fireflies and find the current global best g_*.
end while
```

Fig. 9. Pseudocode of FA.

Cuckoo Search Algorithm

1. *Objective function* $f(x)$.
2. *Initialize parameter* p_a *and population size* $nPop$.
3. *Generate an initial population of host nests.*
4. *Evaluate the fitness of all host nests.*
5. **while** $(t < MaxGeneration)$ or (!stop criterion)
6. *Randomly select a Cuckoo/generate a solution via Lèvy flights.*
7. *Evaluate its fitness* F_i.
8. *Randomly select a nest, e.g.,* x_j.
9. **if** $(F_i < F_{x_j})$,
10. *Then replace* x_j *with the new solution.*
11. **end if**
12. *A fraction* (p_a) *of worse nests are abandoned and new solutions are generated.*
13. *Keep best solutions.*
14. *Rank the solutions and find the current best.*
15. **end while**

Fig. 10. Pseudocode of CSA.

switching angles.

$$OF = 100\frac{(V_D - V_1)^4}{{V_D}^4} + \left(\frac{50}{V_1}\right)^2 \times \left[\left(\frac{V_5}{5}\right)^2 + \left(\frac{V_7}{7}\right)^2 + \left(\frac{V_{11}}{11}\right)^2 + \left(\frac{V_{13}}{13}\right)^2\right] \tag{47}$$

In [177], FA is applied to find the optimized switching angles which minimized the output voltage THD of symmetrical 13-level inverter. The objective function given in Eq. (1) is used, and for verification of algorithm, this algorithm is experimentally validated on symmetrical 13-level inverter

4.7. CSA

CSA is first proposed by Deb and Yang [178] (Fig. 10). This algorithm is inspired by two natural behaviors. The first is the obligate brood parasitic behavior of some cuckoo species, and the second is the lèvy flight behavior of birds and fruit flies. Cuckoo birds laid their eggs in the nest of other birds, mostly from different species, for proper breeding. The eggs of cuckoos generally hatched earlier than the host eggs. The first hatched cuckoo chick blindly propels the rest of the eggs out of the host nest, thereby increasing its share of food provided by the host nest bird. The basic rules of this algorithm are presented as follows.

1. Each cuckoo laid only one egg at a time in any nest by random selection.
2. The best nest with high-quality eggs is survived for the next generation.
3. The available host nests are fixed in number, and the probability of recognizing the cuckoo eggs by host bird is $p_a \epsilon (0,1)$. If the host bird recognized these alien eggs, then it will either throw the eggs away from its nest or it will simply abandon the nest and build a new one in another location.

The host nest contains eggs, which represent solutions and cuckoo egg is a new solution. However, for the next generation, only high-quality solutions are survived. The cuckoo egg is generated using Eq. (48). After obtaining the cuckoo egg, its fitness is compared with that of a randomly selected egg from the nest. If the fitness of the cuckoo egg is better than that of the selected egg, then the cuckoo solution is replaced with the host nest solution. At the end of each iteration, fraction p_a of the worst nest is abandoned and new solutions are generated.

$$x_i^{t+1} = x_i^t + \alpha \oplus L\grave{e}vy(\lambda) \tag{48}$$

where α is the step size, and its value is dependent on the scales of an interested problem. The term $L\grave{e}vy$ indicated lèvy flight, which is responsible for random walks. Lèvy flight played an important role in the exploration of a search space and it is calculated using Eq. (49):

$$L\grave{e}vy \sim u = t^{-\lambda} \quad 1 < \lambda \le 3. \tag{49}$$

The CSA is first proposed in [179] to eliminate the unwanted low-order non-triplen harmonics from 7- and 9-level inverter. The firings angles are calculated using the objective function given in Eq. (30) for type-a output voltage waveform. The proposed algorithm showed better performance in controlling parameters, satisfying constraints and finding the global minimum solution in a short number of iterations. To verify the effectiveness, the proposed algorithm is experimentally validated on a 7 and 11-level inverter. In [180], modified CSA minimizes the THD present in the output voltage of 5-level flying capacitor inverter using the objective function given in (1). The object of proposed algorithm is to calculate the optimized switching angles without using any controller or measuring capacitor voltage and current. In this research, the modeling of harmonic elimination is also improved because it considered the effects of blanking time, dissipative snubbers, the computational time required in processors and the delay due to the gate-drive circuits.

4.8. BOA

BOA is First developed by Yang [181] (Fig. 11). This algorithm is inspired by the echolocation behavior of Bats. The Bats used echolocation, which worked like sonar that helped them to find a prey or a target. Bats emitted a pulse of extremely loud sound and made decisions based on the echo, which reflected from surrounding entities. From the echo information, bats can sense the type of object, its distance, and barriers in the background. The bats randomly fly at position x_i with constant frequency f_{min}, velocity v_i, loudness A_0, and varying wavelengths λ to search their target or food. Bats automatically adjusted the frequency or wavelength of their released pulses based on the information of their target and controlled the emission pulse rate $r \epsilon [0,1]$. BOA used the same concept, terms of velocity and position as used in PSO. For each bat, velocity and position are calculated using Eqs. (50) and (51), respectively:

$$v_i^{t+1} = v_i^t + (v_i^t - x_*) f_i \tag{50}$$

$$x_i^{t+1} = x_i^t + v_i^{t+1} \tag{51}$$

where f_i is the fixed frequency calculated using Eq. (52), and x_* is the position of the current global best.

$$f_i = f_{min} + (f_{max} - f_{min})\beta \tag{52}$$

Where β is the uniformly distributed random number generated

Bat Optimization Algorithm

1. *Objective function* $f(x)$.
2. *Initialize parameters,* f_i *at* x_i, r_i, A_i, *and population size* $nPop$.
3. *Generate an initial population of bats.*
4. **while** $(t < MaxGeneration)$ or (!stop criterion)
5. *Generate new solutions by adjusting the frequency and updating velocities and locations.*
6. **If** $(rand > r_i)$,
7. *Then select a solution among the best solutions.*
8. *Generate a local solution around the selected best solution.*
9. **end if**
10. *Generate a new solution by flying randomly.*
11. **if** $(rand < A_i \ \& \ f(x_i) < f(x_*))$,
12. *Then accept the new solution.*
13. *Increase* r_i *and reduce* A_i.
14. ***end if***
15. *Rank the bats and find the current best* x_*.
16. **end while**

Fig. 11. Pseudocode of BOA.

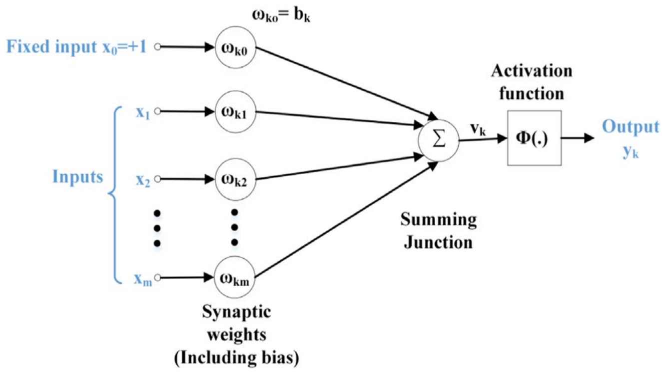


Fig. 12. Nonlinear model of a neuron k.

between [0, 1]; and f_{min} and f_{max} are the minimum and maximum frequency ranges, respectively. The term f_i controlled the range and pace of bat movement.

The BOA is first proposed in [182] to find the firings angles, eliminates the unwanted harmonics from type-a output waveform for 7-level inverter using the objective function given in Eq. (30). The performance of proposed algorithm is found better than GA and BA in terms of eliminating unwanted harmonics and controlling fundamental at required level. Also; experimentally, the percentage of THD in output voltage is found less than GA and BA.

4.9. ANN

ANN is inspired from the natural neural network of the human nervous system [65]. The human brain is a highly complex, nonlinear, and parallel computer that has estimated 10 billion neurons and each is averagely connected with 10,000 other neurons. The ANN is designed and modeled in the same way as brain executed a particular task. The ANN used a massive interconnection of neurons to achieve good performance. The nonlinear model of a neuron is shown in Fig. 12.

The network of neurons gets the knowledge from the environment through the learning process and updated their synaptic weights to achieve the objective. The model present in Fig. 12 is mathematically expressed by Eq. (53).

$$y_k = \Phi(v_k) \tag{53}$$

Where v_k is calculated using Eq. (54).

$$v_k = \sum_{j=1}^{m} w_{kj}x_j + b_k \tag{54}$$

Where w_{kj} represent the strength of synapse and b_k is the bias whose function is to increase or decrease the value of v_k. The activation function $\Phi(.)$ is applied to convert v_k into scalar output y_k. In general, one neuron even with multiple inputs is not sufficient to solve complex engineering problems. Therefore, for solving difficult problems neurons are used to operate in parallel which formed as a layer. Furthermore, multiple layers can also be cascaded to achieve complex objectives.

The ANN is first proposed in [183] to minimize the low-order harmonics in real-time from solar panel connected MVSI. This technique replaces lookup tables with the online calculation of optimized switching angles. In this study, the switching angles are calculated for an 11-level inverter for varying input DC sources and each cell is connected with a solar panel having a capacity of 195 W. In this research, GA is used to solve the transcendental equations and find the switching angles offline which are used as a dataset for training the ANN. In [184], adaptive neuro-fuzzy inference system (ANFIS) is proposed to predict the optimum modulation index and calculated the optimized switching angles which eliminate 3rd order harmonic from the 5-level stand-alone photovoltaic connected inverter. In this study, NR method is used to obtain the data set for ANFIS analysis and the DC-DC converter is used to regulate the DC voltages obtained from the solar panel. In this research, each cell of the full bridge is connected to 4 solar panels having a capacity of 85 Wp. In [185], adaptive selective harmonic minimization technique based on the ANN is proposed for an 11-level inverter for varying input DC sources. In the proposed method, GA is used to calculate the switching angles offline for different values of input DC sources using the objective function given in Eq. (55). In real-time, ANN is applied to determine the switching angles for present values of input DC sources.

$$OF = k_1|V_1-110|+k_2|V_5|+k_3|V_7|+k_4|V_{11}|+k_5|V_{13}| \tag{55}$$

In [186], radial basis function neural network is proposed to eliminate harmonics from diode-clamped MVSI. This method is found simple, accurate and has high convergence speed, in addition, the proposed method is easy to implement. The 7-level diode clamped inverter is experimentally designed and implemented to validate the algorithm. In [187], ANFIS is proposed to eliminate voltage harmonics present in the output voltage of MVSI. Based on the voltage variation, ANFIS generated the switching angles which produced output voltage with reduced THD. In [53], generalized hopfield neural network (GHNN), i.e., a single layer recurrent network, is applied to minimize the 5th, 7th, 11th and 13th order harmonics from the output voltage of single phase inverter. In this method, the energy function is designed and set of ordinary differential equations (ODEs) are obtained which represent the behavior of GHNN. In the proposed method, ODEs are solved using Runge-Kutta fourth-order method which gives switching instant for continuously varying modulation indexes. In [87], ANN is proposed to control the speed of induction motor in electrical vehicles. The proposed algorithm is experimentally implemented on FPGA to generate the switching angles in real-time to validate the algorithm. In the whole range of speed variation, the proposed algorithm efficiently eliminates the unwanted harmonics and control the fundamental voltage at the required level. In [86], ANFIS/(Constant Voltage Maximum Power Point Tracker) algorithm is proposed to minimize the harmonics in the output of PV connected inverter. In the case of asymmetrical condition, the proposed algorithm simply converts non-equal DC sources into equal DC source. For symmetrical condition, PSO and NR are used to find the switching angles offline which minimized the THD. For PSO, the objective function given in Eq. (56) is used for finding the optimized switching angles. The proposed method is experimentally validated on 11-level PV fed inverter with induction motor drive using Xilinx Spartan®-3A DSP FPGA controller.

$$OF = 100 \times \frac{|V_5| + |V_7| + |V_{11}| + |V_{13}|}{|V_1|} \tag{56}$$

In [188], ANN is applied to improve the power quality of solar PV system. This algorithm is experimentally validated on the 15-level 3 kWp solar PV inverter. In [189], a hybrid ANFIS is proposed to minimize the low-order harmonics in 7-level inverter using the objective function given in (17) for Microgrids. In this algorithm, BA is applied to calculate the optimized switching angles offline which are used as a data set for training ANFIS.

5. Performance comparison and discussion

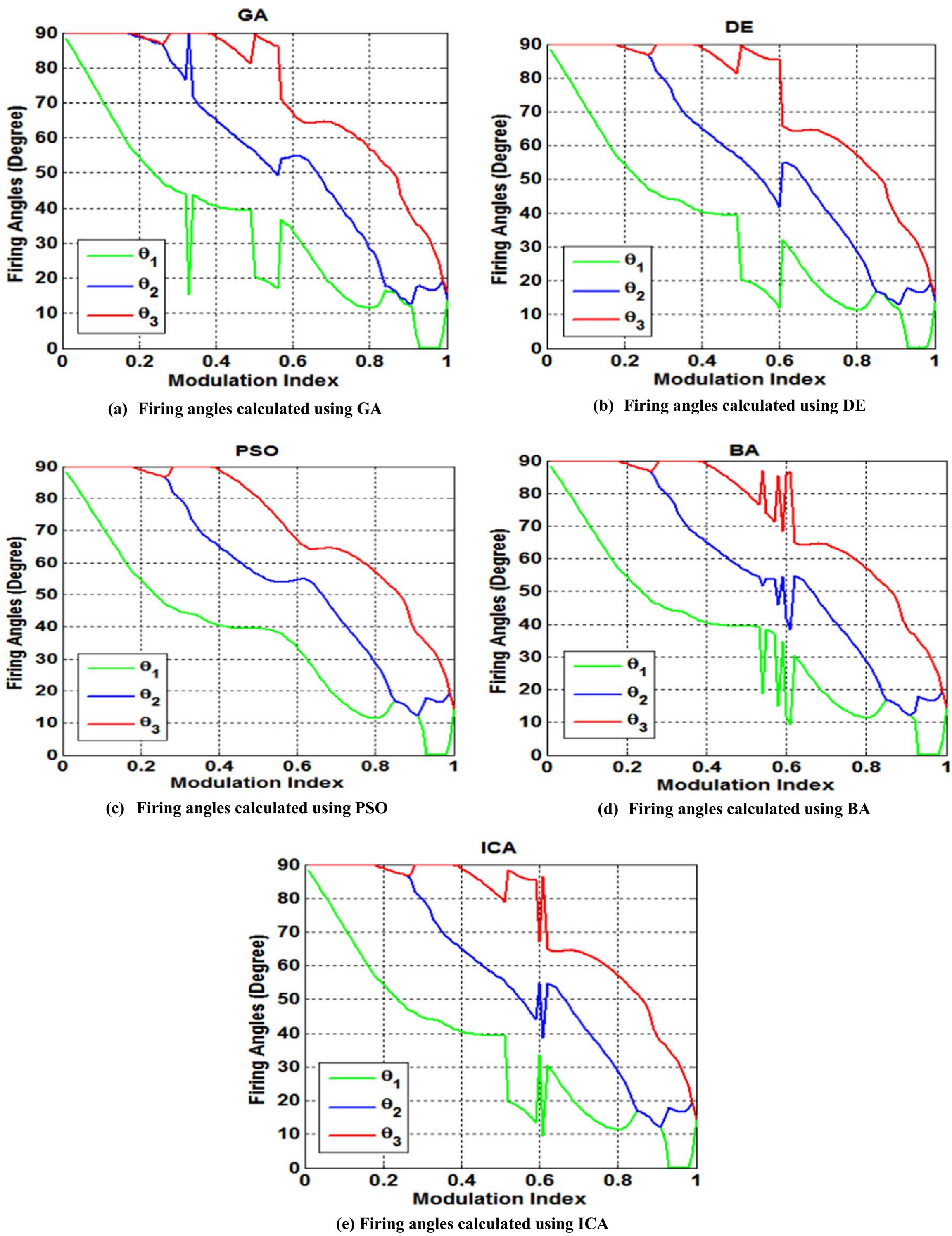
In the literature, researchers mostly validated their algorithms on different levels of the inverter and chose their own objective function to calculate the optimized firing angles. Also, they considered different values of control parameters to tune the algorithm. Each work claimed the superiority of their proposed method on various grounds and aspects. Thus, it is difficult to assess the true performance of any algorithm from the existing literature.

Various BIAs have been proposed in the literature to find the optimized firing angles. However; for performance comparison, only

Table 4
Parameters values of different BIAs.

Algorithm	GA		DE		PSO			BA	ICA	
Control parameter	*CR*	*MR*	*CR*	*F*	c_1, c_2	w_{max}	w_{min}	*L*	β	ξ
Value	0.8	0.2	1	0.8	2	0.9	0.4	150	2	0.05

the top five algorithms, namely, GA, DE, PSO, BA, and ICA, are selected. These algorithms are chosen based on their popularity and prominent features. The performance of these algorithms is analyzed and compared using the same objective function and the expected best values of the control parameters. These algorithms are programmed to calculate the firing angles of 7-level inverter for type-a output waveform.



(a) Firing angles calculated using GA

(b) Firing angles calculated using DE

(c) Firing angles calculated using PSO

(d) Firing angles calculated using BA

(e) Firing angles calculated using ICA

Fig. 13. Firing angles obtained for each M using selected BIAs for 7-level inverter.

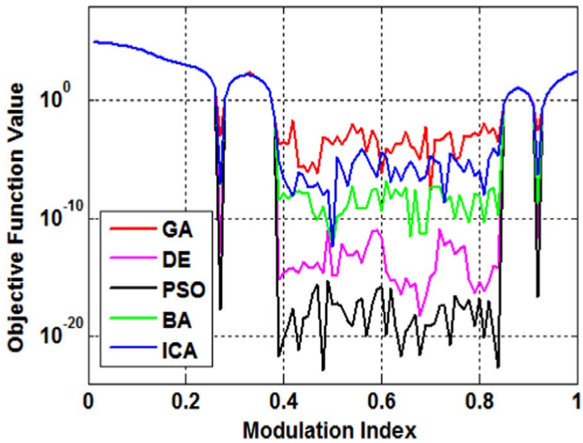


Fig. 14. Objective function value achieved for each M using the selected BIAs.

Table 5
Comparison results.

Algorithm	GA	DE	PSO	BA	ICA
Accuracy	10^{-2}	10^{-10}	10^{-15}	10^{-7}	10^{-4}
Execution time (s)	503	277	65	881	40
Convergence speed CDF (10^{-15})	0%	14%	48%	0%	0%
Number of control parameters	2	2	4	1	2

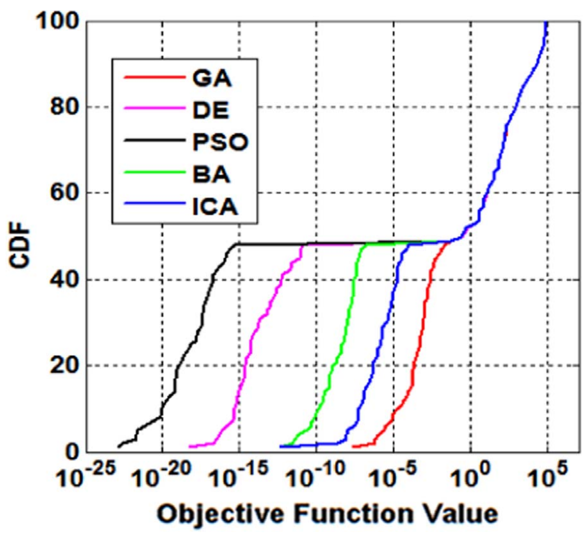


Fig. 15. CDF curve of GA, DE, PSO, BA, and ICA.

5.1. Evaluation of the five BIAs

To evaluate the performance of selected BIAs, the objective function given in Eq. (17) is used to find the firing angles. For a fair comparison, all the algorithms have the same population (100) and executed up to maximum 500 iterations. The firing angles are calculated for the range $0<M\leq1$ with a step size of 0.01. MATLAB is used to program the algorithms and analyzing the results. PSO based on a ring topology and DE based on the DE/rand/1 mutation scheme is used in programming. The values of control parameter used in selected BIAs are presented in Table 4.

5.2. Results

5.2.1. Firing angles

The firing angles (θ_1, θ_2, θ_3) calculated using selected BIAs of 7-level inverter are shown in Fig. 13(a)–(f). The firing angles in Fig. 13 exhibit

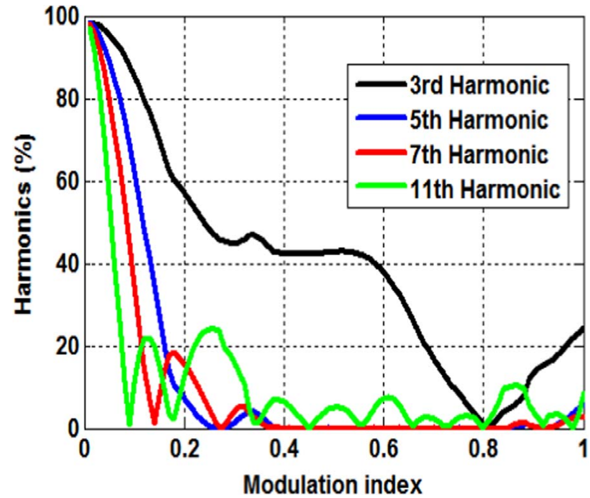


Fig. 16. Harmonic response.

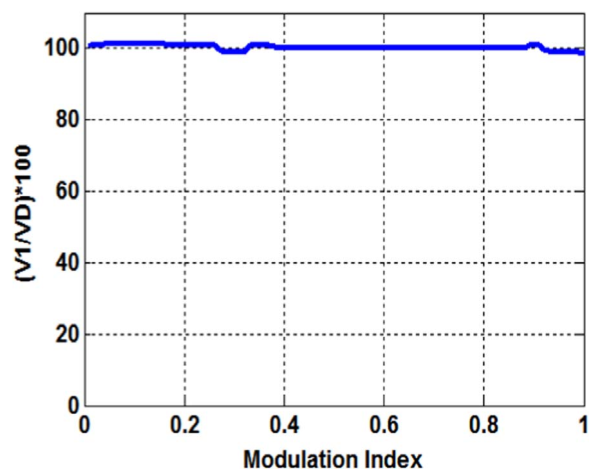


Fig. 17. Fundamental (%) achieved at each modulation index.

Table 6
Switching angles calculated using PSO at M = 0.8.

M	θ_1	θ_2	θ_3	Objective function value
0.8	11.5042	28.7169	57.1060	1.18e − 18

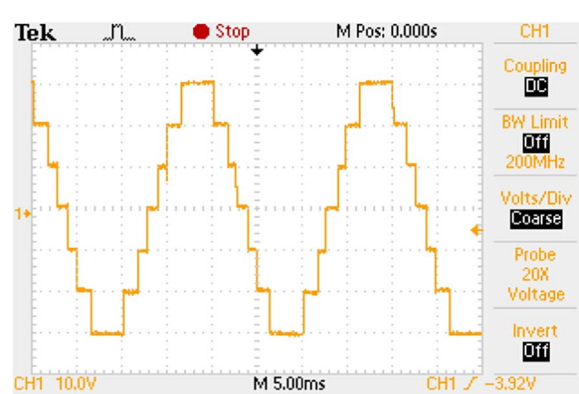


Fig. 18. Phase voltage generated at M = 0.8.

the capability of controlling fundamental at the required level with the additional advantage of eliminating the 5th and 7th order harmonics from the inverter output voltage. The BIAs have the potential to produce single or multiple solutions for each M as shown in Fig. 13.

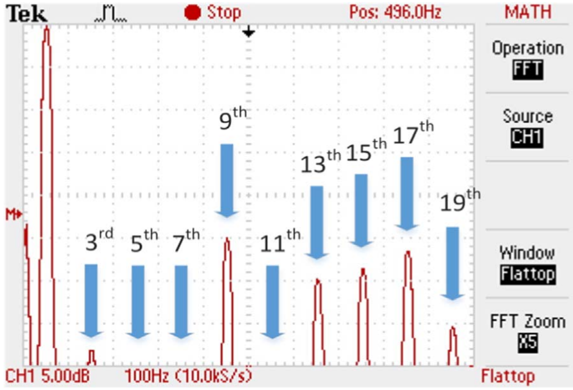


Fig. 19. Harmonic spectrum of experimental output phase voltage at M = 0.8.

This Figure illustrates that selected BIAs produced different sets of firing angles in M range from 0.5 to 0.61. Thus, this band has multiple solutions, which eliminated the unwanted low-order harmonics. With the exception of this band, nearly all the algorithms produced approximately the same set of firing angles.

5.2.2. Accuracy of firing angles

The accuracy of a firing angle depends upon the value of an objective function. Fig. 14 shows the objective function value that has been achieved for each M using the selected BIAs.

Fig. 14 illustrates that PSO minimized the objective function value to below 10^{-15} for the majority of the M range, which has solutions. DE exhibits the second best performance by minimizing the objective function value to below 10^{-10}. BA, ICA, and GA minimized the objective function value to below 10^{-7}, 10^{-4}, and 10^{-2}, respectively. Hence, PSO minimized the objective function to the smaller value compared with the other algorithms for most of the M range. From Fig. 14, it is shown that the firing angles calculated using PSO are more précised, optimized, and accurate. The summary of all the comparison results is presented in Table 5.

5.2.3. Computational complexity

The complexity of an algorithm is assessed by its execution time. Table 5 shows the program execution time of each algorithm (in seconds). This Table indicates that ICA required the shortest time to find the firing angles compared with the other algorithms, whereas BA required the longest time. PSO has taken a slightly longer time than ICA, whereas its execution time is less than DE, GA, and BA.

5.2.4. Convergence speed

The convergence speed is the measure of how fast an algorithm finds the global minimum solution. Fig. 14 shows that the convergence speed of PSO is faster than those of the other algorithms. To further understand the concept of convergence speed, the cumulative distribution function (CDF) is applied to the objective function value obtained from GA, DE, PSO, BA, and ICA. The CDF curve determined the probability of the objective function value (X) that reached to or below the specific value (x) as given in Eq. (57):

$$CDF(x) = P(X \leq x). \tag{57}$$

The CDF curve of GA, DE, PSO, BA, and ICA are shown in Fig. 15 and summarized in Table 5.

Table 5 clearly shows that the CDF (10^{-15}) of PSO is 48%, which indicates that 48% of the M range is below the value of 10^{-15}, whereas it is 14% for DE and 0% for BA, ICA, and GA.

5.2.5. Number of control parameters

Less number of control parameters makes algorithm easier to understand and tune. The control parameters of each algorithm are listed in Table 5. BA did not require any control parameter except L; whereas DE, GA, and ICA used two, and PSO used four control parameters.

Table 5 shows that PSO calculated highly optimized firing angles in less number of iterations with less computational time than GA, DE, and BA. However, PSO used four control parameters, which are more than those of the other algorithms. DE is the second best algorithm; however, it required a longer time than PSO and ICA and its computational cost further increased when applied to a high number of levels or firing angles derived for type-b output waveforms. ICA has taken minimal time to find optimized angles; however, this technique produced low-quality solutions compared with PSO, DE, and BA. The performance of ICA can be improved by combining it with NR, MADS, or any other local search algorithm.

6. Simulation and experimental results

From the comparison results, the performance of PSO algorithm is found superior as compared to other algorithms for eliminating the unwanted harmonics from MVSI. Therefore; in this section, firing angles derived from PSO algorithm (Fig. 13(c)) are considered only for harmonic analysis and experimental validation. Fig. 16 shows the harmonic response of 7-level inverter by applying the firing angles calculated from PSO algorithm. Fig. 17. Shows the percentage of fundamental achieved at each M.

From Fig. 16, it is shown that the 5th and 7th order harmonics are completely eliminated from the output voltage of 7-level inverter for M (0.27, 0.39–0.84, and 0.92). Also, the fundamental voltage is maintained at required level as shown in Fig. 17. To confirm the simulation results, the switching angles found from PSO are experimentally applied on single phase 7-level inverter. The experiment is performed at M = 0.8 and respective switching angles are shown in Table 6.

The MVSI is designed for 50 Hz output frequency, and each H-Bridge cell is connected to 10 V constant DC supply. The Tektronix TDS 2024B oscilloscope is used to measure the output phase voltage and performed the FFT analysis. Fig. 18 shows the output phase voltage of 7-level inverter at M = 0.8 using the switching angles given in Table 6. Fig. 19 shows the harmonic response of output phase voltage at M = 0.8.

From Fig. 19, it is shown that the 5th and 7th harmonics are successfully eliminated from the 7-level inverter output phase voltage which confirmed the simulation results.

7. Conclusion

This review paper presented the comprehensive study of the SHEPWM technique for solving the HE problem of the inverter and special attention is given to BIAs. The information presented in this paper will be useful for researchers and engineers who are working on the energy conversion systems particularly from RE sources. In this paper, the working principle of nine well-known BIAs has been explained in detail with their HE applications in inverters. Besides this, different objective functions have been also presented in this paper which are often used by researchers, which will help new researchers and practitioners to design a better and efficient algorithm for HE. Furthermore, the performance of the five best BIAs is critically evaluated by various factors, such as accuracy, computational complexity, convergence speed, and a number of control parameters. The comparison results indicated that the performance of PSO is superior to those of the other algorithms in terms of accuracy and convergence speed. Its computational cost found less than those of BA, GA, and DE. For varying input DC sources such as PV, PSO is found suitable for generating efficient data set for training ANN. PSO has been found simple and easy to implement in real-time. In last, PSO can be effectively utilized for finding the firing angles for type-b output waveform in inverters for any number of levels. It has also been found that all BIAs are easy to realize and implement, and they exhibited good potential to solve the HE problem in inverters, particularly in MVSI. This feature is highly desirable for RE applications.

Acknowledgments

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