Selective Harmonics Elimination in Multilevel Inverter Using Bio-Inspired Intelligent Algorithms

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***Abstract*— Multilevel inverters are powerful electronic devices that are used for the conversion of DC input voltage into AC output voltage and mostly used in medium and high voltage operations. In these operations, pulse width modulation (PWM) frequency is distorted because of electromagnetic interference (EMI) and switching losses which are caused by dv/dt stress. To achieve a pure sinusoidal waveform at output of multilevel inverter is a primary purpose so that a smaller number of harmonic contents are produced. Selective harmonic elimination PWM technique is used in cascaded multilevel inverter for the mitigation of lower harmonics by solving non-linear transcendental equations and maintains the required fundamental voltage. An objective function is derived from SHE problem to calculate switching angles. For the solution of objective function, optimization approach such as bio-inspired intelligent algorithms are used. In this paper, Genetic Algorithm (GA), Particle Swarm Optimization (PSO) and Bee Algorithm (BA) are used to determine the optimum switching angles for cascaded multilevel inverters to get low total harmonic distortion (THD) in output voltage. These computed angles are analyzed in MATLAB simulation model to authenticate the results. And there will be direct comparison among these algorithms.**

Keywords*— *Multilevel inverter, total harmonic distortion, Bio-inspired algorithm, Pulse width modulation.

I. INTRODUCTION

Nowadays, Multilevel Inverters (MLI) has got more attention in medium and high voltage utilization [1]. Also, it has low switching frequency deprivation, high efficiency, Low Electro-Magnetic Interference (EMI), and less dv/dt stress on the switches [1]. Multilevel inverters have less Total Harmonic Distortion (THD) because of their stepped waveform as compared to square wave inverters. It has three main topologies namely Diode Clamped (DC) [2], Flying Capacitor (FC) [3], and Cascaded H-bridge Inverter (CHI) [4] along with a separate DC source. Among these topologies, the cascaded inverter is modular in design and simple in control and the power circuit consists of the cascaded link of 'x' number of single-phase inverter with an output level of (2x+1) [5]. Practically, CHI contains separate dc sources but unfavorable to maintain the magnitude of these dc sources with different voltage levels [6]. Therefore, it may cause a problem in maintaining source voltages during the charging and discharging gap [7].

To improve the inverter performance such as output voltage and harmonic mitigation, different modulation techniques have been suggested [8] notably Sinusoidal Pulse Width Modulation (SPWM) [9] and Space Vector Control (SVC) technique[10]. However, the PWM technique is not effective to minimize the undesired lower order harmonics completely. Therefore, another technique likely Selective Harmonic Elimination Pulse Width Modulation (SHEPWM) or programmed PWM is considered to minimize the low order harmonics [11]. The main advantage of this technique is the adaptation of firing angles in multilevel inverters to suppress the low order selective harmonics. Nonetheless, the main issue in this technique is to find the set of solutions of nonlinear transcendental equations in obtaining the firing angles[12].

Several conventional methods have been suggested for the solution of these nonlinear transcendental equations that can be divided into two sets of solutions. In iterative methods, specifically Newton Raphson (N-R) method [15] need good initial guesses which should describe the solution motif. Also, the N-R method perceives solutions for initial guesses. Therefore, it is hard to find a solution with the increase in inverter levels. Another systematic approach is considered namely the resultant theory method [16] that is used for harmonic suppression in inverters. However, it has drawbacks i.e., convoluted and blows of time. If there is a change in voltage levels, it requires a new mathematical expression. Similarly, the Homotopic algorithm [18] is used but it finds only one solution for nonlinear equations.

To overcome the above-mentioned shortcomings, a novel method is proposed, and its advantages are as follows:

- The evolutionary algorithms have the potential to find the optimum solution for different values of modulation index because of high convergence to its solution, and eliminate the lower order harmonics from multilevel inverters.
- This method produces switching angles for the minimization of nonlinear equations.
- The evolutionary algorithms are very simple, easy to implement and derivative free for any level of inverter, and are free [19].

Considering these advantages, GA [20], BA [21], and PSO [22] are simulated to minimize the THD [23] of the output

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voltage of 7 level inverter. Specifically, these algorithms have high convergence to their solutions and no need for initial guesses. Moreover, they are easy to implement, fast, robust, and less controlled parameters. Additionally, the derived objective function from the SHE problem is minimized to calculate the firing angles while low order harmonics of an inverter are controlled within permissible limits. The effectiveness of these algorithms is compared based on the observed results [25].

II. Methodology

A seven-level inverter is considered which has three H-bridge cells as displayed in Fig. 1. These cells are connected in series with each other and it stretches stair-case output voltage (Fig 2). Also, various output voltage levels are produced by every H-bridge cell (+Vdc, 0 and -Vdc) and measurement of voltage levels '2x+1' is used. Where 'x' shows the number of bridges in a seven-level inverter which is equal to 3. This type of inverter is also called three-level inverters because of its H-bridges count. It has no clamping diodes, absence of voltage balancing capacitors, tight control, modular design, and easy adjustment of output voltage levels. Moreover, Switches Q1, Q2, Q3, and Q4 are conducted one time in a cycle of frequency to reduce the switching losses in a circuit. For the three-phase configuration, the output of these three converters is connected in Y or Δ manners [26], and the firing angles α_1, α_2, and α_3 are selected as shown in Fig. 2 for the elimination of certain order of harmonics.

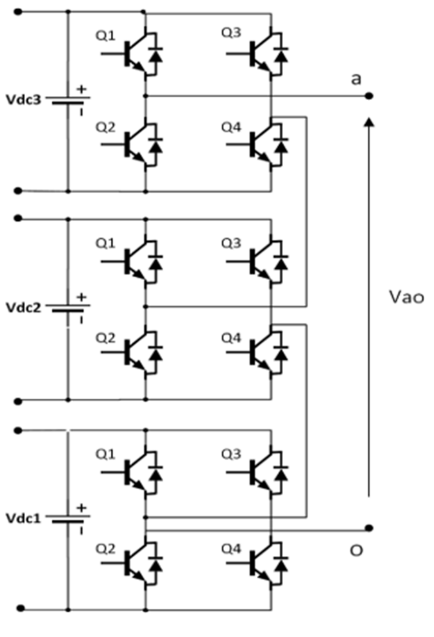

Fig 1. Topology of seven-level inverter

A. Selected Harmonic Elimination PWM (SHEPWM)

To eliminate the even-numbered harmonics, selective harmonic elimination PWM exploits the quarter-wave symmetry that is useful for the reduction of computational burden [29]. Moreover, triplen harmonics are absent from three-phase line to line voltage. Therefore, only odd-numbered, and non-triplen harmonics are required to eliminate (such as 5th 7th 11th 13th, etc). Fig. 1 Represents a 7-level inverter output voltage waveform and α1, α2, and α3 are three variables used in it and (V_{dc1}, V_{dc2}, V_{dc3}) are considered equal in magnitude. By using Fourier series expansion, the voltage magnitude of n^{th} order harmonic can be found as shown in (1) [27]. Fig. 2 represents a 7-level inverter output voltage waveform where α_1, α_2, and α_3 are three variables used in it, and Vdc1, Vdc2, Vdc3 are considered equal in magnitude.

$$V(\omega t) = \sum_{n=1,3,5}^{\infty} \frac{4V_{dc}}{n\pi}(cos(n\alpha_1 \pm cos(n\alpha_2) \pm .... \pm \sin n\omega t) \quad (1)$$

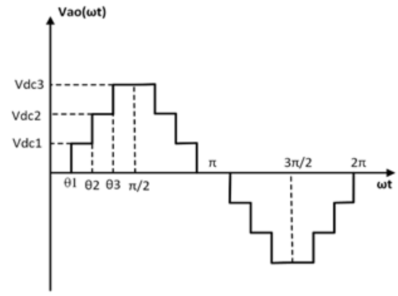

Fig 2. Output voltage waveform of seven-level inverter

Above switching angles $\alpha_1 - \alpha_s$ should satisfy the condition of (2)

$$0 \le \alpha_1 \le \alpha_2 ... \le \alpha_s \le \frac{\pi}{2} \quad (2)$$

In Eq. (1) both the positive and negative sign shows the rising and falling edge of output voltage waveform. For the mitigation of low order harmonic content, the switching angles α_1 - α_s are employed to choose in such a way that the fundamental frequency remains same. In cascaded multilevel inverter the number of harmonics required to eliminate are 'x-1' here, 'x' shows number of H-bridges. For example, in seven level inverter 5th and 7th harmonics are required to minimize by satisfying (3)

$$\begin{cases} cos(\alpha_1) + cos(\alpha_2) + cos(\alpha_3) = (3\pi/4)M \\ cos(5\alpha_1) + cos(5\alpha_2) + cos(5\alpha_3) = 0 \\ cos(7\alpha_1) + cos(7\alpha_2) + cos(7\alpha_3) = 0 \end{cases} \quad (3)$$

B. Proposed Genetic (GA) Algorithm

This algorithm depends on genetic operators like crossover, mutation, and reproduction etc. For the minimization of given

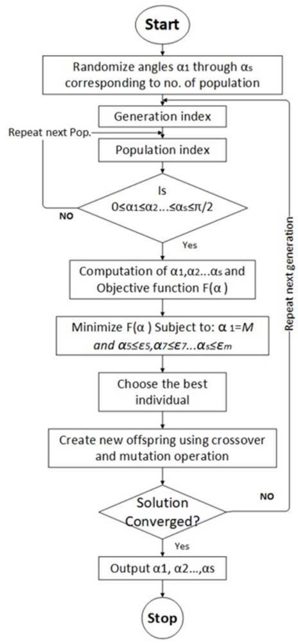

Fig. 3. Flow chart of Genetic Algorithm

objective function, it does not require any derivative functions. In genetic algorithm, optimization is the process of maximization. For the minimization of any required function the negative optimization is to be employed. To find a local minima of function f(z_1, z_2,…z_k) using GA, first each element of the given function is converted into binary or fluctuating number sequence. In this research, binary number sequence is proposed [1]. A generalized flow chart of GA is expressed in Fig. 3.

C. *Proposed Genetic (GA) Algorithm*

For the calculation of switching angles in multilevel inverter, this evolutionary algorithm based on foraging act of bees in nature is implemented [28]. Naturally three types of bees are considered in bees swarm; employed bees, on-looker bees and scout bees. In 1st phase employed bees are the first platoon, it carries direction of site and instructions that how much nectar is available. Employed bees convey their collected information to onlooker bees with the help of dance. Dancing of employed bees at a specific time tells other bees about the quantity of nectar available. If mass nectar is enough then it is selected by on looker bees otherwise, refused to go there. Scout bees find new search spaces for food. Exploring new food resources is controlled by scout bees while employed bees and on looker bees are also utilized in search of food. Suppose that food sources are the only solution to the problem in bee algorithm. Then in optimization problem food origin is an area 'A' it represents optimization variables. A generalized flow chart of BA is expressed in Fig. 4.

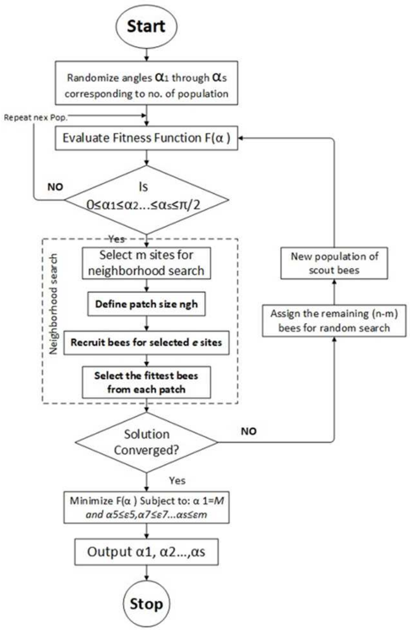

Fig. 4. Flow chart of BA Algorithm

D. *Proposed Particle Swarm Optimization (PSO) Algorithm*

This method is influenced by social behavior of flocking of birds also with schooling of fish etc. in a swarm. Each individual is called particle in a population [30]. For optimization problem, every shred of whole population searches its own best position in multidimensional space. Now a days, many researchers use this optimization methodology for the solution of nonlinear equations [21]. A generalized flow chart of PSO is expressed in Fig. 5 [31].

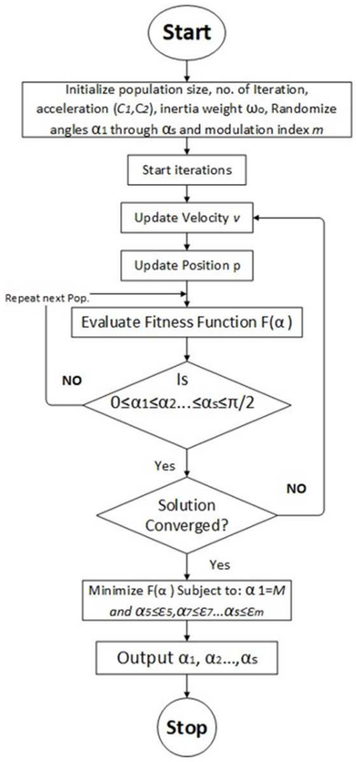

Fig. 5. Flow chart of PSO Algorithm

III. IMPLEMENTATION

The Bio-inspired intelligent algorithms are widely used to find switching angles and the necessary programs are written in MATLAB software [32]. For the mitigation of low order harmonic content, Equation 3 must be solved to find unknown α_1, α_2, and α_3 while the fundamental frequency remains satisfied. The Objective function used in this case is described as (4)

$$f(\alpha_1, \alpha_2, \alpha_3) = 100 \times \left[\left|M - \frac{|V_1|}{3V_{dc}}\right| + \left(\frac{|V_5|+|V_7|}{3V_{dc}}\right)\right] \quad (4)$$

Where V_1 is the fundamental voltage, V_5 and V_7 are the 5th and 7th order voltage which needs to be minimized. By using this objective function, the 5th and 7th harmonic in cascaded seven-level inverter can be eliminated. The 3rd order harmonic and even harmonics are suppressed in a 3-phase inverter automatically. It is stated previously, different types of bio-inspired intelligent algorithms have been used for the mitigation of selected harmonic content in multilevel converters. The researchers make their objective functions for finding switching angles for various levels of the inverter with different tuning parameters of algorithms. However, the comparison of three bio-inspired algorithms (GA, PSO, and BA), which is proposed in this work for harmonic mitigation in seven level inverters, are shown in TABLE 1.

TABLE I. COMPARISON RESULTS

Algorithm	**GA**	**PSO**	**BA**
Population size	100	100	100
No. of iteration	300	300	300
Run time	150 sec	120 sec	180 sec
Complication of code	low	low	moderate
Converging property	moderate	high	moderate
Control parameters	CR, MR	c_1,c_2 w_{max},w_{min}	L
Precision	10^{-2}	10^{-15}	10^{-7}

These three algorithms are chosen because of their popularity, performance, and prestigious attributes. The objective function that evaluates the execution of BIAs is given in equation 13, the switching angles for seven-level inverters can be found within a range of 0<M<1, and controlling properties are given in the above Table. The objective function values for different bio-inspired algorithms show the accuracy of algorithms that how much it converges to its solution (Fig. 6). Notably, PSO shows more convergence to its objective function that is used in Equation 13 by eliminating the selected 5th and 7th harmonic.

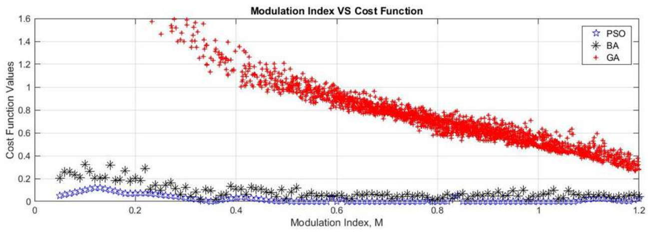

Fig. 6. The objective function values of different algorithms

Based on the previous settings, switching angles of seven-level inverter (α_1, α_2, α_3) are produced by the bio-inspired intelligent algorithm and represented in Fig. 7, Fig. 8, and Fig. 9. These switching angles can control or maintain the fundamental component of the output voltage. Moreover, these angles have the advantage to mitigate the 5th and 7th harmonic components from the output of the seven-level inverter. The switching angles showed in the figures justifies that these algorithms have multiple solutions for every *M.* Also, these figures demonstrate that bio-inspired intelligent algorithms generate more solution sets of switching angles in the range between 0.6 and 1.0 of M. Due to this range; it eliminates low order harmonic content from the inverter output.

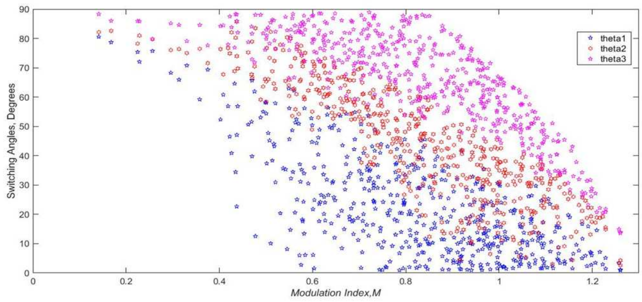

Fig 7. Calculated switching angles by using GA

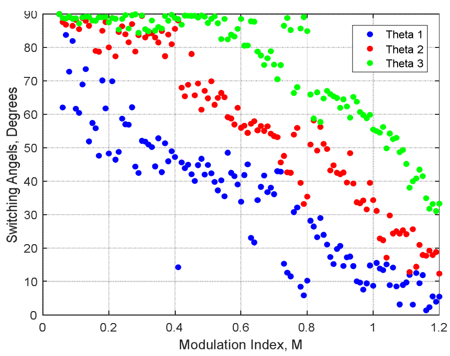

Fig 8. Calculated switching angles by using BA

Further, the harmonic content and modulation index are demonstrated in Fig. 10, Fig. 11, and Fig. 12 that are produced by bio-inspired intelligent algorithms. Specifically, Fig. 11 illustrates the genetic algorithm that reduces the 5th and 7th harmonics and maintains the fundamental voltage significantly. The other two waveforms describe the minimization of THD produced by BA and PSO algorithm in a specific interval of *M* between 0.5 and 1.0 values when the THD is nearly equal to zero and some of these values are used to mitigate the 5th and 7th harmonic from the output of the multilevel inverter.

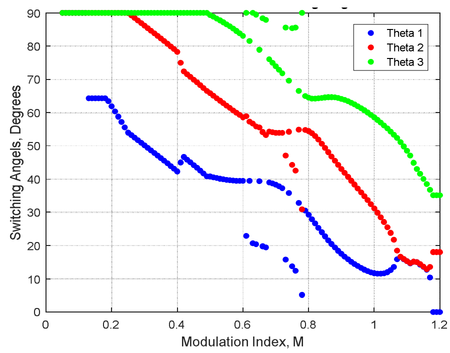

Fig 9. Calculated switching angles by using PSO

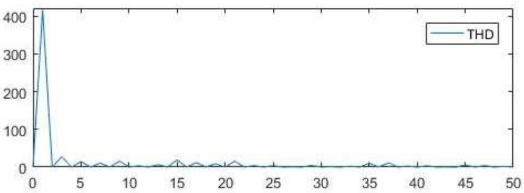

Fig 10. THD waveform of GA

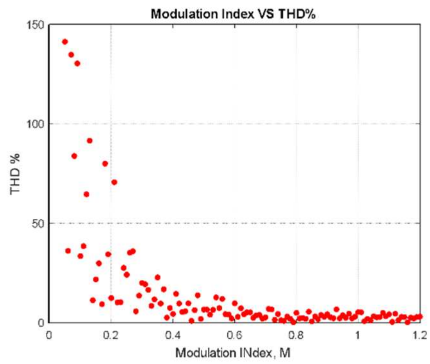

Fig 11. THD waveform of BA along with *M*

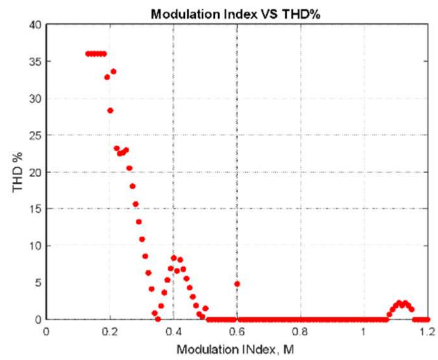

Fig 12. THD waveform of PSO along with *M*

IV. Results and Discussions

For minimization of low order harmonic content, the switching angles obtained from PSO, GA, and BA (after solving the nonlinear transcendental equations 3) are placed in the Simulink model of cascaded H-bridge converter and the respective FFT analyses are evaluated. It is noted that the PSO eliminated 5th and 7th order harmonic utterly compare to other algorithms. The THD value of PSO, GA, and BA are computed as 12.56%, 13.03%, and 12% respectively employing (5) [33]

$$THD = \sqrt{\sum_{n=5,7,11,\ldots}^{\infty} V_n^2}\,/V_1 \qquad (5)$$

Where 'V_1' is fundamental voltage angles obtained from these three algorithms which are displayed in TABLE II.

TABLE II. ANGLES AND THD OF GA, BA, AND PSO.

Angles	GA	BA	PSO
α_1	4.82°	9.26°	11.64°
α_2	25.60°	25.83°	27.084°
α_3	44.13°	54.04°	56.142°
THD	13.03%	12.56%	12.01%

The angles extracted from algorithms are used to switch IGBTs in each H-bridge module at pre-decided time steps. Each H-bridge is linked with a separate DC voltage source and switching signals are produced by Digital Signal Processor (DSP) and these signals are given to the gate drivers to switch ON and OFF IGBTs. Further, the simulated output waveform of the cascaded seven-level converter is shown in Fig. 13. It is recorded between the magnitude of voltage and time having a time interval from 0 to 0.12. It is noted that the total DC voltage (V_{dc}) of 24 volts is applied to the inverter which gives sinusoidal AC output voltage. It is noted that the THD of the GA algorithm is logged as 13.03%. Also, 5th and 7th order harmonics are suppressed appropriately by the GA algorithm as demonstrated in Fig. 14. Similarly, 5th and 7th order harmonics are suppressed precisely from the application of the BA algorithm (Fig. 15). Contrarily, the same order harmonics are completely mitigated meritoriously by the application of the PSO algorithm (Fig. 16) and shows more convergence to the desired solution as compared to the other two algorithms.

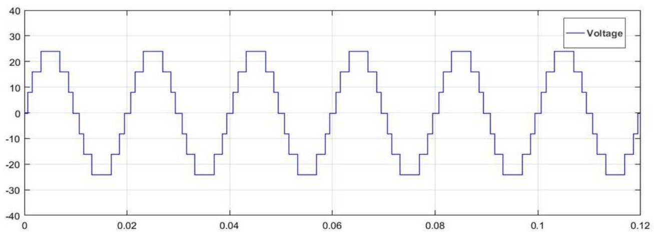

Fig 13. AC output of seven-level inverter

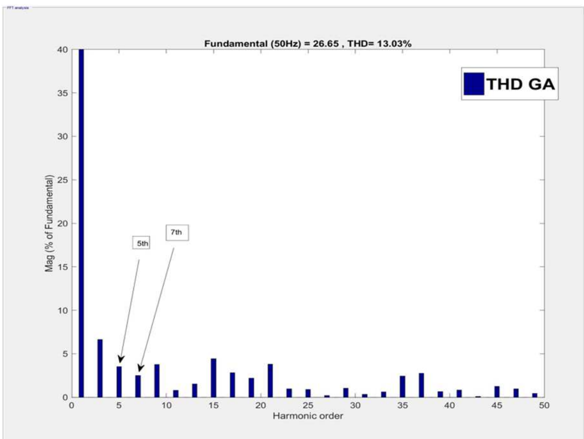

Fig 14. Harmonic spectrum of Genetic Algorithm (GA)

Consolidating the observed results, the proposed method finds the fidelity of switching angles by considering the values of the objective function. These values are extracted from each

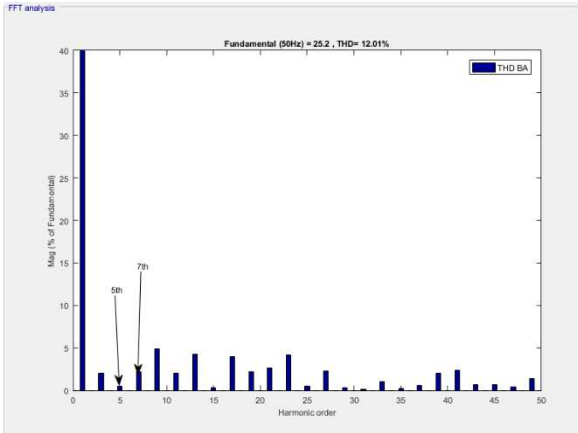

Fig 15. Harmonic spectrum of Bee algorithm (BA)

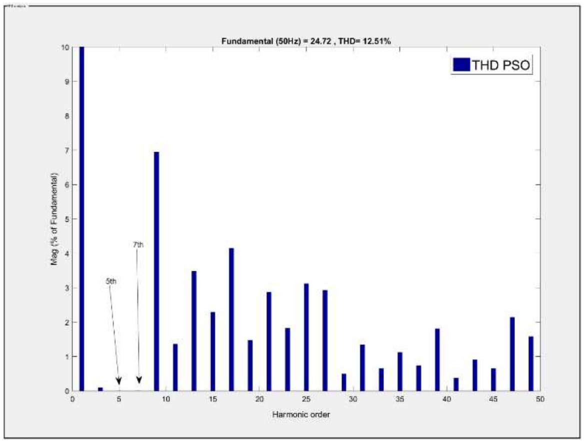

Fig 16. Harmonic spectrum of Particle Swarm Optimization (PSO)

M by utilizing the algorithms. It is shown in Table 1 that PSO has minimized the value of objective function beneath the 10^{-15} for the values of *M*. BA and GA have the value of objective function below the 10^{-7} and 10^{-2} respectively. Table 1 shows the computation time for each algorithm that indicates the complexity of algorithmic code i.e., less run time shows that the code complexity is less and shorter to get switching angles. Also, the convergence speed describes how fast the algorithm finds the global minima. Further, PSO has a high converging speed as compared to the other two algorithms because of low code complexity. Because of high convergence speed, less code complexity, and high precision, PSO finds highly optimized switching angles when compared with GA and BA.

V. CONCLUSION

In this work, optimal switching frequencies for low order harmonics in seven level full-bridge converters are investigated. For this purpose, selective harmonic elimination pulse width modulation technique has been designed. During the implementation process, non-linear transcendental equations are generated. To obtain a solution for these equations, bio-inspired intelligent algorithms are used such as GA, PSO, and BA. These three algorithms could solve non-linear equations and provided a solution set of switching angles through an offline process. With this technique, lower frequency content especially 5th and 7th harmonics could be eliminated. Moreover, the FFT analysis and the comparison among these three algorithms showed the superiority of PSO over GA and BA in terms of THD minimization. The proposed model could be implemented on hardware structure for real-time verification scenarios in future applications.

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