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Executing The ICMPPSO Optimization Algorithm to Minimize Phase Voltage THD of Multilevel Inverter with Adjustable DC Sources

Hadi Vadizadeh[1], Ebrahim Afjei[2], Alireza Siadatan[3]
[1,3]Department of Electrical Engineering, West Tehran Branch, Islamic Azad University, Tehran, Iran
[2]Department of Electrical and Computer Engineering, Shahid Beheshti University G.C., Tehran, Iran
([1]hadi66engineer@gmail.com, [2]e-afjei@sbu.ac.ir, [3]a_siadatan@wtiau.ac.ir)

Abstract- A multilevel Inverters have many advantages such as reduced Harmonics, no need for a transformer, cost and loss reduction. In this paper the multilevel inverter with adjustable DC sources is used for THD optimization. THD is a very important factor to determine the loss rate in the network equipment. Therefore, the calculation of its accurate value has a direct effect on the decisions for reduction of losses and measuring of network parameters etc. In most of prior papers for calculation of THD, approximate methods which uses a limited number of the harmonic orders is employed. In this paper, an accurate method is presented for the calculation of phase voltage THD (PVTHD). An accurate formula of PVTHD is calculated by a novel method. An advanced algorithm for switching technique, based on the Formulation of PVTHD is presented. Also, for optimization of PVTHD, angles are calculated by Intelligent Coefficient Multi-Population Particle Swarm Optimization (ICMPPSO). Finally, in order to display the effects of the new methods, new techniques are compared with approximate methods, for a 5 level, a 13 level and a 15 level inverters and comparison results are presented. MATLAB software is used for programming and simulation to accomplish this task.

Keywords- *Multilevel Inverter, Adjustable DC Sources, Accurate Phase Voltage THD, ICMPPSO Algorithm, Accurate formula of PVTHD*

I. INTRODUCTION

One of the most important advantages of the multilevel inverters is the reduction of the harmonics in output waveforms without increasing the frequency, or reduction of output power of inverters. In many applications, it is desirable to get an AC output voltage with varying frequency and amplitude via inverters [1, 2]. The variable speeds AC motor drive system is one of the major areas of application for the variable frequency inverter [3, 4]. Various pulse width modulation (PWM) methods for multi-phase VSIs, have been developed for generating a sinusoidal output voltage [5]. In addition, in FACTS devices [6-8], Distributed Generation applications [9, 10] and renewable energy sources [11, 12] use of multilevel structure.

The well known Switching PWM techniques to reduce the harmonics in the output waveform of the inverter, such as SVPWM[1] [13], SHEPWM[2] [14, 15], and OMTHD[3] [16, 17] have been developed. By considering the large numbers of the levels in multilevel inverter to reduce the production harmonic volume, the SHEPWM technique is suggested that the low Switching loss and low harmonic are its benefits. In OMTHD methods the aim is to optimize the THD without any emphasis on special harmonics. The methods presented in this paper, are very useful for OMTHD technique in multilevel inverter with unequal DC sources.

In this paper, some new methods are presented to calculate the accurate Phase Voltage THD (PVTHD[4]) and in addition the THDM[5] modulation technique is presented. In THDM method, at first, should be extracted a accurate formula of PVTHD, then calculates optimal angles by analytically or intelligent methods, So, in this paper Improved Multi Population Particle Swarm Optimization (ICMPPSO[6]) technique is used for obtaining optimal angles for accurate PVTHD formula.

To demonstrate the effectiveness of the new methods, these new accurate methods are compared with the approximate methods which have been calculated the approximate value of PVTHD to 49^{th} [18] and 97^{th} [19] order harmonic. Require tests have been done for the efficient and accurate calculation of new proposed methods and formulas. In this paper, the main goals are to show that the approximate method is not suitable to calculate of PVTHD, and shown the ICMPPSO is a powerful optimization algorithm.

This paper includes the following parts. In the second section are offered Cascaded structure for Multilevel inverter. The third section is expressed calculation of PVTHD. Then in the fourth section are shown simulation results and a comparison between the new results with previous results. Finally in the fifth Section will be presented conclusion of this paper.

[1] Space Vector Pulse Width Modulation
[2] Selective Harmonics Elimination PWM
[3] Optimal Minimization of Total Harmonic Distortion
[4] Phase Voltage THD
[5] THD Minimization
[6] Intelligent Coefficient Multi-Population Particle Swarm Optimization

II. Cascaded Multilevel Inverter with Adjustable DC Sources

This type of inverters is divided into three general categories, The multilevel inverter with diode clamped, The multilevel inverter with flying capacitor and finally, The multilevel cascaded inverter with separate DC sources (SDCSs). In this paper, is used of multilevel Cascaded Inverter with Separated DC Sources Structures [20]. A single phase M level structure of this inverter is shown in Fig. 1. The multilevel inverter using a cascaded inverter with SDCSs synthesizes a desired voltage from several independent sources of DC voltages, which may be obtained from either battery, fuel cells, or solar cells. So, an output voltage waveform can be generated by summation of the output voltage of each cell.

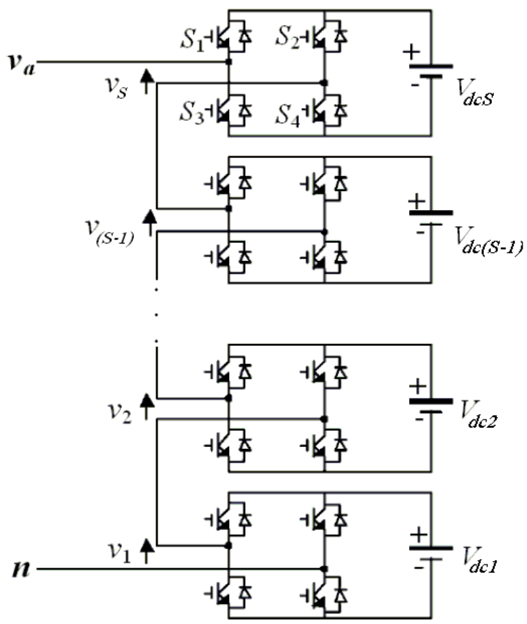


Fig. 1: Single-phase structure of a multilevel cascaded inverter.

Each SDCS is associated with a single-phase full-bridge inverter. This Structure has extreme advantages compared with another structure of inverters: least number of elements to produce the same waveform compares with another structure of inverters, eliminate of clamping diodes and etc. These advantages that have made it attractive in power conditioning systems and medium to high power drive applications [21]. The control in cascaded structure is more simpler than another structure of inverter, unlike the Diode Clamped and Flying capacitor inverters, each phase can be controlled separately and in addition, it also does not require the central controller, in other words the cascaded structures have only one independent controller on each phase.

Each separate DC source is linked with a single phase full-bridge inverter. The Different combination of 4 key S_1 to S_4 in each cell of the inverter can produce 3 different levels of voltage ($+V_{dc}$, $-V_{dc}$, 0). In this topology, the number of output phase voltage levels is defined by m=2S+1, where S is the number of DC sources. For example, a 7-level inverter has 3 SDCS. The quarter-wave symmetric waveform is used in this paper [22, 23]. The voltage waveform which is shown in Fig. 2, has S switches angles in quarter-wave α_1, α_2, …, $\alpha_{(s-1)}$, α_s and 4S switching angles, α_{4S}, in each cycle. In this Paper, the DC voltages are assumed to be adjustable.

$$V_{dc1} \neq V_{dc2} \neq \cdots \neq V_{dc(S-1)} \neq V_{dcS} \tag{1}$$

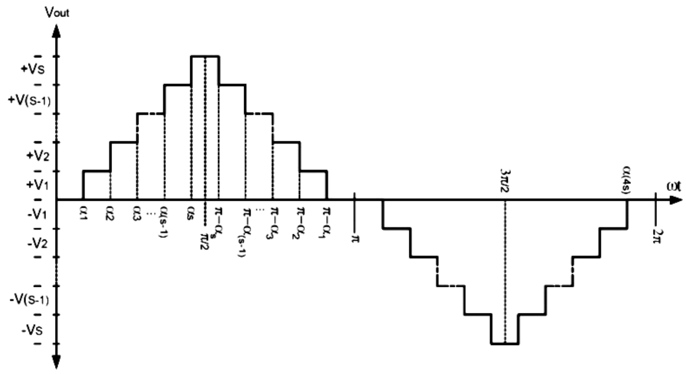


Figure 2. The output waveform of phase voltage in multilevel inverter with an S number of SDCS as series-connected

Each cell is turned on and turned off in suitable angle. The first cell is turned on in α_1 angle, the second cell is turned on in α_2, etc. Then the first cell is turned off in π-α_1 angle, the second cell is turned off in π-α_2, etc. Finally is obtained output waveform with minimum THD.

III. Calculation Of Phase Voltage THD

A. The Traditional and Conventional Method

The The Fourier series of Multilevel waveform is as follows:

$$V(\omega t) = \sum_{n=1}^{\infty} V_n \cdot Sin(n\omega t) \tag{2}$$

V_{an} is the amplitude of the harmonic components of voltage, where are supposed DC sources as equal:

$$V_n = \begin{cases} \dfrac{4}{n\pi} \displaystyle\sum_{k=1}^{S} V_{dck} \cos(n\alpha_k) & for\ odd\ n \\ 0 & for\ even\ n \end{cases} \tag{3}$$

Where S is the number of Full-Bridge cells. In this method, PVTHD formula can be extracted by the following equation:

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} V_n{}^2}}{V_1} \tag{4}$$

Since, the even harmonics are removed, because of half-wave symmetric, Eq. (5) Is extracted from Eq. (4) For the PVTHD as follows:

$$THD = \frac{\sqrt{\sum_{n=3,5,7,9,11,...}^{\infty} V_n{}^2}}{V_1} \tag{5}$$

Most papers use of this approximate method to calculate of PVTHD. This approximates method is not accurate enough, and the user is forced to consider some limited harmonics from the *3th* harmonic to limited values such as *49th* and *97th*. However, this method is somewhat appropriate for applications that not require high accuracy but is not accurate enough and do not take account the remainder harmonics.

B. First Proposed Method, New Technique for Accurate Calculation of PVTHD

Ref. [21] has shown that Eq. (6) Is the equivalent form of (4) which can be used to compute THD. To calculate the accurate value of PVTHD, the formulas (6 and 7) are used.

$$THD = \sqrt{2\left(\frac{V_{rms}^2}{V_1^2}\right)-1} \tag{6}$$

Where, V_{rms} is Root Mean Square (RMS) of voltage and is given by:

$$V_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} V^2(\alpha)d\alpha} \tag{7}$$

The voltage in these formulas, is the phase voltage (V_a). By considering the specific form of the stepped voltage of multi-level inverter, the step function can be used to produce V_a.

$$U(\alpha)=\begin{cases}1 & if \ \ \alpha>0\\ 0 & if \ \ \alpha<0\end{cases} \tag{8}$$

Because of the symmetry, V_a can be written as follows:

$$V_a(\alpha) = p(\alpha) - p(\alpha-\pi) \tag{9}$$

Where, *p(α)* is as follows:

$$\begin{aligned} p(\alpha) &= V_{dc1}U(\alpha-\alpha_1)+V_{dc2}U(\alpha-\alpha_2)+... \\ &+V_{dck}U(\alpha-\alpha_k)-V_{dck}U(\alpha-(\pi-\alpha_k))- \\ &-V_{dck-1}U(\alpha-(\pi-\alpha_{k-1}))-...-V_{dc1}U(\alpha-(\pi-\alpha_1)) \end{aligned} \tag{10}$$

According to the Eq. 10 V_a is given versus step function, then V_{rms} and PVTHD will be calculated. At First are taken angles as input, then the integration of V_a^2 is performed versus obtained angles and THD is gained. The proposed solution in here is determined the angles, and then compute THD through step function. For integrating by notice to the particular stepped that type of phase voltage, the rectangular method is recommended with $\theta_i+\theta_{i-1}$ length. This method could be used for all types of application that have ability of writing the program with a PC. Table 1 is presented for the 9-level inverter.

TABLE I. OBTAINED PHASE THD FROM SAMPLE ANGLES FOR 9-LEVEL INVERTER

α_1	α_2	α_3	α_4	THD_{Actual}	THD_{49}	Error Percent
7.2282	22.1766	38.3936	57.4541	8.8327	7.8020	11.6691
V_{dc1}=1.0000 p.u	V_{dc2}=1.0000 p.u	V_{dc3}=0.9361 p.u	V_{dc4}=0.8276 p.u			

The THD_{49} in table 1, is calculated by Eq. (5) Via approximates method till 49^{th} order harmonic. The error percent shows the difference between THD_{Actual} and THD_{49}. In this article another methods based on accurate phase voltage THD formula are presented which whole of them are useful in practical applications.

C. Second Proposed Method, THDM Method By Extracting of Accurate PVTHD Formula

PVTHD formula is extracted of the basic Eq. (5). In other words, should be considered the harmonic limit as a series until infinitely (∞). By substituting the Eq. (3) In Eq. (5) For calculation of the final limit, the main task is a calculation of the following:

$$\sum_{n=3,5,7,9,...}^{\infty} \frac{\cos^2 n\alpha_1}{n^2} \tag{11}$$

After simplification which is shown in Eq. (11), is obtained Eq. (12).

$$\sum_{n=3,5,7,9,...}^{\infty} \frac{\cos 2n\alpha_1+1}{2n^2} = \frac{1}{2}\left(\sum_{n=3,5,7,9,...}^{\infty} \frac{\cos 2n\alpha_1}{n^2} + \sum_{n=3,5,7,9,...}^{\infty} \frac{1}{n^2}\right) \tag{12}$$

So, the main task is calculation of this series:

$$\sum_{n=3,5,7,9,...}^{\infty} \frac{\cos nx}{n^2} \tag{13}$$

For calculation of the limit (13), Fourier series of an auxiliary function is applied (Eq. 14). This function is $y=(\pi-|x|)^2$ in interval $-2\pi<x<2\pi$.

$$(\pi-|x|)^2 = \frac{\pi^2}{3} + \sum_{n=1}^{\infty} \frac{4}{n^2}\cos nx \tag{14}$$

As it is clear from Eq. (14), the limit of Eq. (13) is calculated for natural numbers (even and odd), but it is needed to calculate the limit for odd n. So, the following process is done. Eq. (15) shows the series limit via main function Eq. (14).

$$\sum_{n=1}^{\infty} \frac{1}{n^2}\cos nx = \frac{(\pi-|x|)^2-\frac{\pi^2}{3}}{4} = \frac{(\pi-x)^2-\frac{\pi^2}{3}}{4} \quad 0<x<2\pi \tag{15}$$

For the calculation of series limit for odd n instead of natural n, x in Eq. (15) is replaced with 2x so, Eq. (16) is obtained for even n.

$$\sum_{n=2,4,..}^{\infty} \frac{1}{n^2}\cos nx = \frac{(\pi-|2x|)^2-\frac{\pi^2}{3}}{16} = \frac{(\pi-2x)^2-\frac{\pi^2}{3}}{16} \quad 0<x<\pi \tag{16}$$

By subtracting the Eq. (16) from the Eq. (15), the series limit for odd n is shown in Eq. (17).

$$\sum_{n=1,3,..}^{\infty} \frac{1}{n^2}\cos nx = \frac{(\pi-x)^2-\frac{\pi^2}{3}}{4} - \frac{(\pi-2x)^2-\frac{\pi^2}{3}}{16} \quad 0<x<\pi \tag{17}$$

For calculation the all terms of Eq. (12), Eq. (18) should be solved.

$$\sum_{q=3,5,...}^{\infty} \frac{\cos q2x}{2q^2} \tag{18}$$

For calculation the limits of Eq. (18), Eq. (17) is rewritten for 2x, So, Eq. (19) is obtained.

$$\sum_{n=1,3,..}^{\infty} \frac{1}{n^2}\cos n2x = \frac{(\pi-2x)^2-\frac{\pi^2}{3}}{4} - \frac{(\pi-4x)^2-\frac{\pi^2}{3}}{16} \qquad 0<\text{x}<\frac{\pi}{2} \tag{19}$$

Since, in Eq. (11), V_n in the numerator is calculated for n = 3, 5, ..., ∞, but Eq. (19) and (17) will be obtained the value of summation for n = 1, 3, ..., ∞, So, for calculating of THD_{ph}, Eq. (5) Is written such as Eq. (20) til is used of Eq. (19) for a obtained of accurate PVTHD.

$$THD = \sqrt{\left(\frac{\sum_{n=1,3,5,7...}^{\infty} V_n^{\,2}}{V_1^{\,2}}\right) - 1} \tag{20}$$

Now, according to the V_n in Eq. (3), THD_{ph} for 5 level inverter is obtained by using Eq. (20):

$$THD_{ph} = \sqrt{\left[\frac{1}{(\text{V}_{dc1}\cos\alpha_1 + \text{V}_{dc2}\cos\alpha_2)^2} \times \sum_{n=1,3,5,...}^{\infty}\left(\frac{\text{V}_{dc1}\cos n\alpha_1 + \text{V}_{dc2}\cos n\alpha_2}{n}\right)^2\right] - 1}$$
$$= \sqrt{\left[\frac{1}{(\text{V}_{dc1}\cos\alpha_1 + \text{V}_{dc2}\cos\alpha_2)^2} \times \sum_{n=1,3,5,...}^{\infty}\left(\frac{\text{V}_{dc1}^{\ 2}\cos^2 n\alpha_1 + \text{V}_{dc2}^{\ 2}\cos^2 n\alpha_2}{n^2} + \frac{2\,\text{V}_{dc1}\text{V}_{dc2}\cos n\alpha_1 \cdot \cos n\alpha_2}{n^2}\right)\right] - 1} \tag{21}$$

After simplification which is shown in Eq. (21), is obtained Eq. (22).

$$THD_{ph} = \sqrt{\left[\frac{1}{(\text{V}_{dc1}\cos\alpha_1 + \text{V}_{dc2}\cos\alpha_2)^2} \times \sum_{n=1,3,5,...}^{\infty}\left(\begin{array}{l}\frac{\text{V}_{dc1}^{\ 2}\cos n2\alpha_1}{2n^2} + \frac{\text{V}_{dc1}^{\ 2}}{2n^2} + \\ \frac{\text{V}_{dc2}^{\ 2}\cos n2\alpha_2}{2n^2} + \frac{\text{V}_{dc2}^{\ 2}}{2n^2} + \\ \frac{\text{V}_{dc1}\text{V}_{dc2}\cos n(\alpha_1+\alpha_2)}{n^2} + \\ \frac{\text{V}_{dc1}\text{V}_{dc2}\cos n(\alpha_2-\alpha_1)}{n^2}\end{array}\right)\right] - 1} \tag{22}$$

According to the Eq. (17) and Eq. (19), by substituting them in Eq. (22), the accurate equation of PVTHD is as follows:

$$THD_{ph} = \sqrt{\left[\frac{1}{(\text{V}_{dc1}\cos\alpha_1 + V_{dc2}\cos\alpha_2)^2} \times \sum_{n=1,3,5,...}^{\infty}\left(\begin{array}{l}\frac{V_{dc1}^{\,2}(\pi-2\alpha_1)^2-\frac{\pi^2}{3}}{8} - \frac{V_{dc1}^{\,2}(\pi-4\alpha_1)^2-\frac{\pi^2}{3}}{32} + \frac{V_{dc1}^{\,2}\pi^2}{16} + \\ + \frac{V_{dc2}^{\,2}(\pi-2\alpha_2)^2-\frac{\pi^2}{3}}{8} - \frac{V_{dc2}^{\,2}(\pi-4\alpha_2)^2-\frac{\pi^2}{3}}{32} + \frac{V_{dc2}^{\,2}\pi^2}{16} + \\ \frac{V_{dc1}V_{dc2}(\pi-(\alpha_1+\alpha_2))^2-\frac{\pi^2}{3}}{4} - \frac{V_{dc1}V_{dc2}(\pi-2(\alpha_1+\alpha_2))^2-\frac{\pi^2}{3}}{16} + \\ + \frac{V_{dc1}V_{dc2}(\pi-(\alpha_2-\alpha_1))^2-\frac{\pi^2}{3}}{4} - \frac{V_{dc1}V_{dc2}(\pi-2(\alpha_2+\alpha_1))^2-\frac{\pi^2}{3}}{16}\end{array}\right)\right] - 1} \tag{23}$$

After simplification which is shown in Eq. (23), is obtained Eq. (24).

$$THD_{ph} = \sqrt{\left(\frac{\pi^2}{8}\cdot\frac{(V_{dc1}+V_{dc2})^2 - \frac{2}{\pi}\left[\alpha_1 V_{dc1}^{\ 2} + \alpha_2\left(V_{dc2}^{\ 2} + 2V_{dc2}V_{dc1}\right)\right]}{(V_{dc1}\cos\alpha_1 + V_{dc2}\cos\alpha_2)^2}\right) - 1} \tag{24}$$

If Eq. (22) is developed for the number of more angles α, the general equation of the PVTHD (THD_{ph}) is obtained for Multilevel inverter with Equal SCDS:

$$THD_{ph} = \sqrt{\left[\frac{1}{\left(\sum_{i=1}^{S}\text{V}_{dci}\cos\alpha_i\right)^2} \times \left(\begin{array}{l}\sum_{n=1,3,5,...}^{\infty}\sum_{i=1}^{S}\frac{\text{V}_{dci}^{\ 2}\cos n2\alpha_i}{2n^2} + \frac{\text{V}_{dci}^{\ 2}}{2n^2} + \\ + \sum_{n=1,3,5,...}^{\infty}\sum_{k=1}^{S}\sum_{\substack{L=2\\ L\neq k\\ L>K}}^{S}\frac{\text{V}_{dcK}\text{V}_{dcL}\cos n(\alpha_k+\alpha_L)}{n^2} \\ \sum_{n=1,3,5,...}^{\infty}\sum_{k=1}^{S}\sum_{\substack{L=2\\ L\neq k\\ L>K}}^{S}\frac{\text{V}_{dcK}\text{V}_{dcL}\cos n(\alpha_L-\alpha_k)}{n^2}\end{array}\right)\right] - 1} \tag{25}$$

In Eq. (25), S is the number of Switching angles per quarter wave. By developing Eq. (25) for the 7, 9 and 11 level inverter, and by Substituting Eq. (17) and Eq. (19), is obtained similar some formula. Then by comparison among the obtained formula and by mathematical simples, final a general formula, Finally the accurate PVTHD is obtained as follows:

$$THD_{ph} = \sqrt{\left[\frac{\pi^2}{8}\cdot\frac{\left(\sum_{K=1}^{S}V_K\right)^2 - \frac{2}{\pi}\left[\alpha_1 V_1^{\ 2} + \sum_{j=2}^{S}\alpha_j\left(V_j^{\ 2} + 2V_j\sum_{i=1}^{j-1}V_i\right)\right]}{\left(\sum_{K=1}^{S}V_K Cos\ \alpha_K\right)^2}\right] - 1} \tag{26}$$

Via Eq. (26), there is the possibility of accurate calculation of local and global minimization without the use of intelligent methods, as analytical and numerical with this accurate formula. Also can be used by intelligent methods for obtaining optimal angles for optimization of PVTHD by a new fitness function that is shown in Eq. (26).

D. Third Proposed Method, Employing of IMPPSO Algorithm to minimize PVTHD

Eq. (26) is used for optimization method as a fitness function. The intelligent method based on PSO algorithm is developed in this paper. The correction motion vector for each particle in PSO method is as follows:

$$v_{i+1}^{k+1} = w_i v_i^k + c_1.rand\left(pbest - x_i^k\right) + c_2.rand\left(gbest - x_i^k\right) \quad (27)$$

In Eq. (27), V_i^k is the motion vector of i^{th} particle in k^{th} repetition. V_i^{k+1} is a correction motion vector for i^{th} particle. Rand is a random number in zero till one interval. x_i^k is the current position of i^{th} particle in k^{th} repetition. *pbest* is the best answer of i^{th} particle in all repetition, The index of the best particle among all the particles in the group is represented as gbest. w_i is the weight coefficient for speed vector of i^{th} particle and C_i is the weight coefficient for each particle.

In this paper, use of more population in the main PSO algorithm, which can be determined arbitrary value for N_p parameter, the N_p is number of population. Also in [24, 25] to ensure convergence of the method is used by contraction coefficient *K*, which their value is calculated according to the values of the weighting coefficients that is shown in Eq. (28).

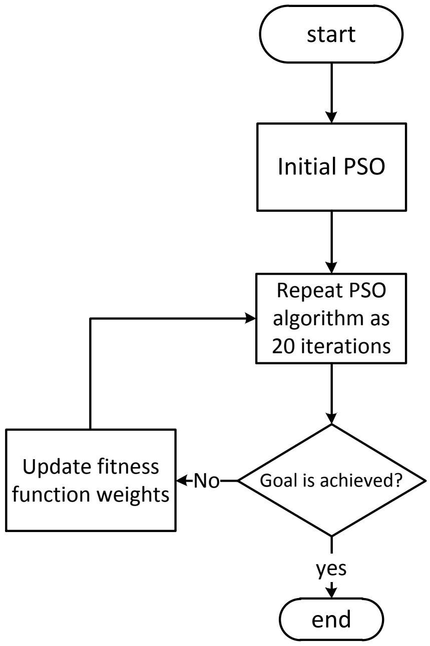
$$v_{i+1}^{k+1} = K*(w_i v_i^k + c_1.rand.(pbest - x_i^k) + c_2.rand(gbest - x_i^k))$$
$$K = \frac{2}{\left|2 - C - \sqrt{C^2 - 4C}\right|} \quad where\ C = c_1 + c_2 \quad and \quad C > 4 \quad (28)$$

In the proposed method, multiple populations are used as parallel to optimize the fitness function. In each step of a repeat, the each population will have been optimized the fitness function as separately, which motion vector for each population is modified as follows:

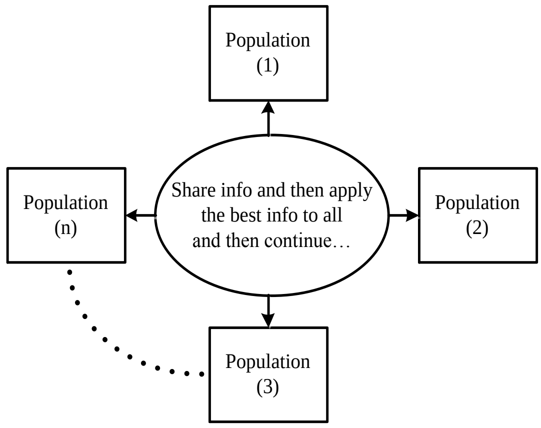
$$v_{i+1}^{k+1} = K*\begin{pmatrix} w_i v_i^k + c_1.rand.\left(pbest - x_i^k\right) + c_2.rand\left(gbest - x_i^k\right) + \\ +c_3.rand.\left(gbest\_total - x_i^k\right) \end{pmatrix} \quad (29)$$

In Eq. (29) coefficient C3, is the weight coefficient of third relationship, which can be determined by trade of technique according to the type of optimization problem. *gbest_total*, is the best value of the *gbest* among all populations in each repetition. In this case, the particles of each population are up to date according to their population and other populations. This new solution increases the scope of the search and the speed of convergence. After repeating process which is considered, the each population will have an optimal solution. The ultimate answer, is the best choice from the different population. It is clear that the increasing of the data volume processing by increase the number of populations.

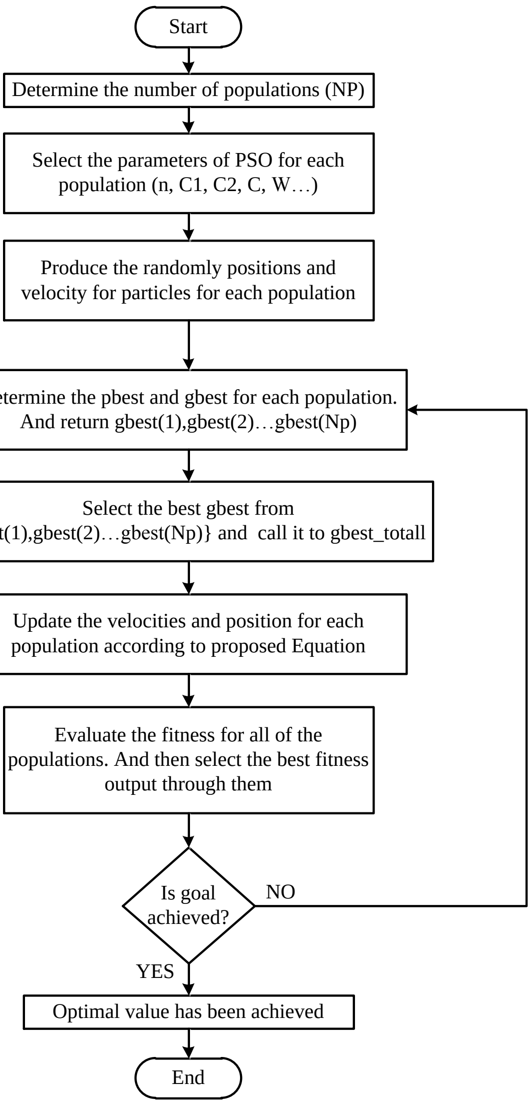
In the ICMPPSO optimization algorithm, the weighting coefficients in the fitness function are updated as intelligent in every 20 iterations. The flow diagram of intelligent update of weighting coefficient is shown in Fig. 3 (a). The procedure to implement the proposed ICMPPSO technique is summarized in the diagram of Fig. 3 (b). The flowchart of the basic operation of the ICMPPSO shown in Fig. 3 (c) is explained as follows:



(a)



(b)



(c)

Fig. 3 (a) The flow diagram of Intelligent Update of Weighting Coefficient (b) Block diagram of the implementation of the proposed ICMPPSO technique (c) Flowchart of ICMPPSO

IV. Simulation Results

A. Comparison Between THDM and Approximate Methods

The proposed Method is validated in previous part. Here, the exact value of THD is compared with the approximate value of THD that considers until 49th harmonic and 97th harmonic. It is shown that the accuracy of approximate method is less than exact method. These methods are named THD_{actual}, THD_{49} and THD_{97}, respectively. Fig. 4 shows obtained values of these three methods for the multilevel inverter with adjustable DC sources versus $0<\alpha<89$.

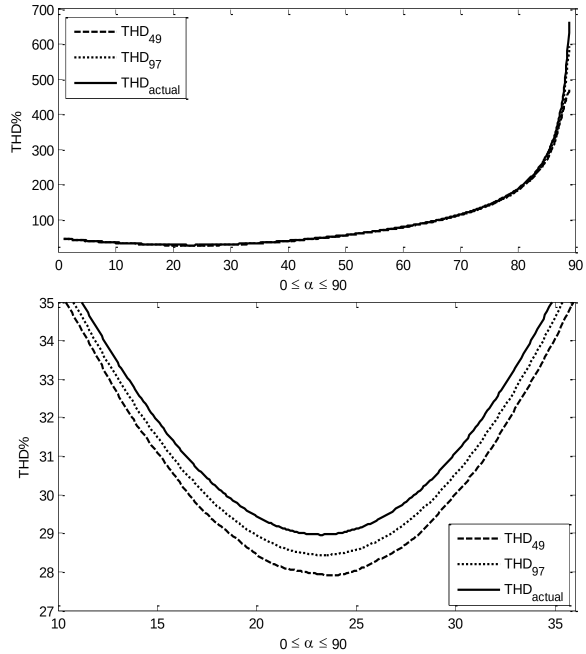


Fig. 4 Obtained values of PVTHD by three methods

Since the differences between approximate methods and exact value are small in comparison with the value of THD, the difference seems to be slight. When the angle approaches to 90 the THD reaches to ∞.

As expected, obtained PVTHD value from exact method is more than others. Obtained PVTHD from approximate method, considering till 49th harmonic, has the least value. The difference between exact PVTHD with two other approximate types is shown in Fig. 5.

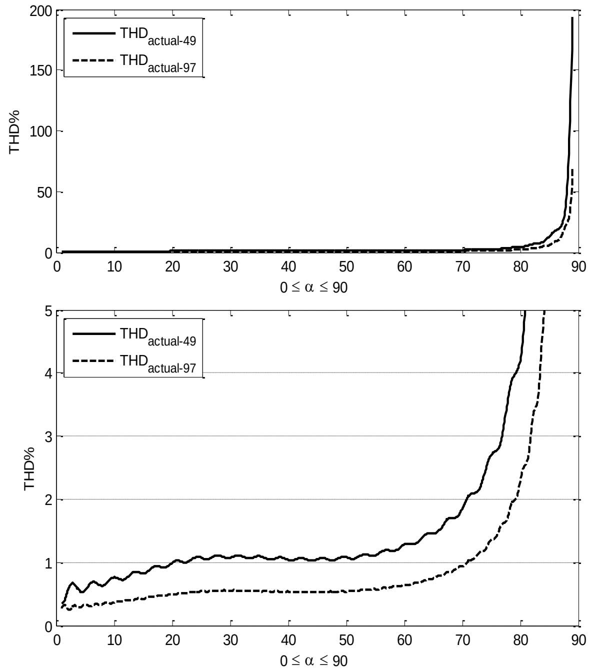


Fig. 5 PVTHD difference between three methods

An interesting point in this figure is that, not only the amount of PVTHD approaches to ∞ for big switching angles, but also the difference between methods approaches to ∞. It is obvious that $THD_{actual-49}$ is more than $THD_{actual-99}$. For angles more than 70 degrees, the difference is more than 2% which is a large value.

Standard IEEE-519 [26] limits the value of THD to a value less than 5 percent to be acceptable, hence an error of 2% is large in comparison with an error 5%, which has 40% of error. However, this difference in angles more than 60 and 30 degrees, reaches to 1.28 and 1.069 with an error of 25.6% and 21.38%, respectively. Also, the percentage of error for THD_{49} is shown in Fig. 6. As a result, the approximate method is not acceptable.

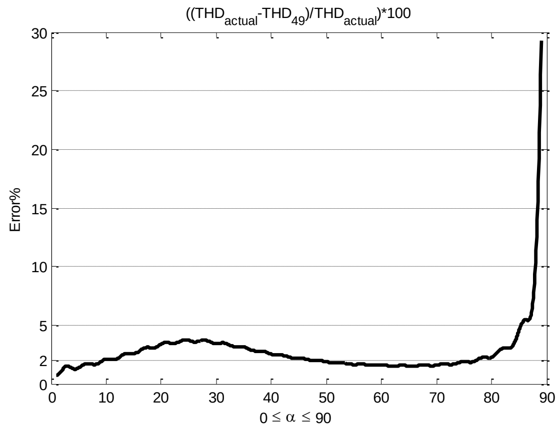


Fig. 6 Percentage of error for THD_{49} in multilevel inverter with Adjustable DC sources

The different values in 56.07 percent of interval of modulation index, are greater than 2% that is unacceptable. For more research, three dimensional curves are presented for the 5 level inverter 0<α1, α2 <85. Fig. 7 is shown the THD values which obtained by accurate method.

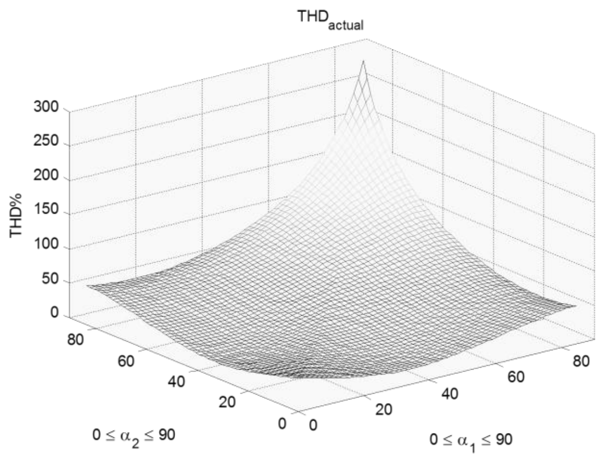


Fig. 7. THD values which obtained by the accurate method versus two angles

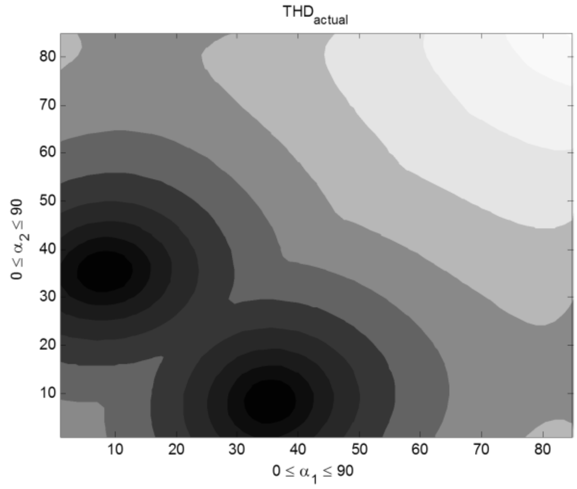


Fig. 8. View the THD contour versus angle

The same amount Surface of THD (Contour), for Fig. 7 is shown in Fig. 8. Dark spots is shown Low values and bright spots is shown larger values of THD_{ph}.

In the following, 3 dimensional curves are presented for Multilevel inverter with two angles, (i.e. $0<\alpha_1,\alpha_2<85$). Figs. 9 and 10 show the absolute and percentage of errors, respectively. The greatest differences between actual value with the approximate value as well as are visible for angles greater than 18 degrees.

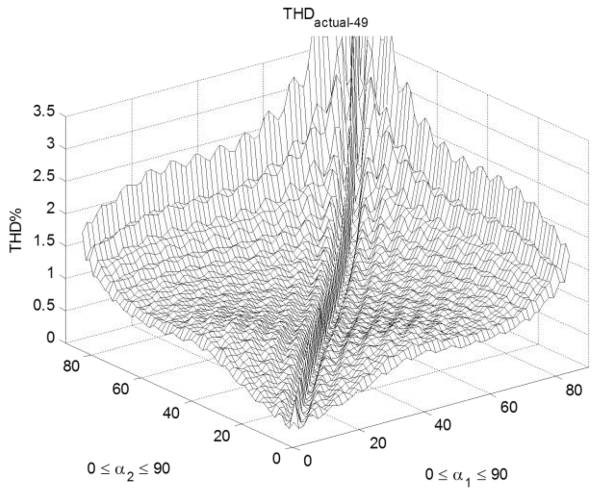


Fig. 9 THD difference between approximate and exact methods

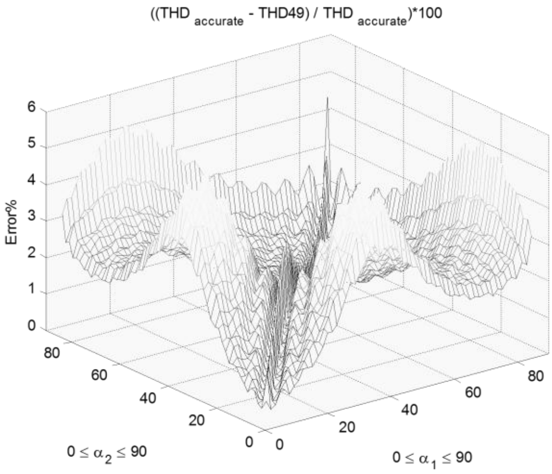


Fig. 10 Percentage of error for THD_{49}

The sample survey of PVTHD for multilevel inverter with adjustable DC sources, is extracted by ICMPPSO algorithm which are shown in Table (I).

TABLE II. THE SAMPLE SURVEY OF PVTHD FOR 5 LEVEL INVERTER

THD	Switching Angles	Adjustable DC Sources	Error Percent
	α_1=13.4520 α_2=42.6606	V_{dc1}=0.9788 V_{dc2}=0.8937	
THD_{49}	15.2626		6.8237
THD_{97}	15.8547		3.2091
THD_{10^6}	16.3803		0.00031
THD_{Actual}	16.3804		0
THD	α_1=14.50 α_2=41.60	V_{dc1}=0.6247 V_{dc2}=0.5704	**Error Percent**
THD_{49}	15.3518		6.8444
THD_{97}	15.9598		3.1552
THD_{10^6}	16.4797		0.0003
THD_{Actual}	16.4798		0

B. The Results of IMPPSO Method

For shown the accurate methods Effectiveness, PVTHD for 13 and 15 level inverter are optimized by Improved Multi Population PSO. The extracted results in this case, indicate the effectiveness and superiority of this method into the previous approximate methods.

In Table (III) and Table (IV) has presented the obtained results for the 13 and 15 level inverters, respectively. The error percentage is calculated as Eq. (30):

$$\left(\frac{THD_{Actual} - THD_{49}}{THD_{Actual}}\right)\times 100 \qquad (30)$$

The same results that are obtained from Tables (III) and (IV), have shown that the unacceptable difference between actual and approximate THD in 13 and 15 level Inverter.

TABLE III. THE OPTIMAL RESULTS FOR THE 13 LEVEL INVERTER

α_1=4.9187 α_2=14.9192 α_3=25.3989 α_4=36.6086 α_5=49.0162 α_6=64.0404 V_{dc1}=1.0000 V_{dc2}=1.0000 V_{dc3}=0.9970 V_{dc4}=0.9530 V_{dc5}=0.8940 V_{dc6}=0.7826		
THD	**Magnitude %**	**Error Percent**
THD_{49}	4.9030	19.0360
THD_{97}	5.4845	9.4336
THD_{10^6}	6.0557	0.00087
THD_{Actual}	6.0558	0

TABLE IV. THE OPTIMAL RESULTS FOR THE 15 LEVEL INVERTER

α_1=4.4044 α_2=13.0188 α_3=21.4991 α_4=30.8334 α_5=40.8667 α_6=51.2955 α_7=65.2548 V_{dc1}=0.7174 V_{dc2}=0.6862 V_{dc3}=0.6637 V_{dc4}=0.7086 V_{dc5}=0.6068 V_{dc6}=0.6173 V_{dc7}=0.5722		
THD	**Magnitude %**	**Error Percent**
THD_{49}	4.2593	18.9181
THD_{97}	4.6826	10.8595
THD_{10^6}	5.2530	0.00099
THD_{Actual}	5.2531	0

In these Table are shown approximate THD which is calculated till 10^6 order harmonic, although the large number of harmonic order is considered in this calculation, but there is a small percent error into the accurate PVTHD. It is certainly an impossible calculation of these values for Harmonics as manually and spent a lot of time for the computer.

The data for a 13 and a 15 level inverter are presented in table V. A Validation and Comparison between these methods is shown in Table VI.

TABLE V. VALIDATION AND COMPARISON BETWEEN ALL METHODS

13 level inverter	α_1= 4.738	α_2= 14.382	α_3= 24.448	α_4= 35.369	α_5= 47.879	α_6= 63.036	--
	V_{dc1}= 0.999	V_{dc2}= 1.000	V_{dc3}= 0.990	V_{dc4}= 1.000	V_{dc5}= 0.956	V_{dc6}= 0.856	--
15 level inverter	α_1= 4.005	α_2= 12.096	α_3= 20.442	α_4= 29.272	α_5= 38.952	α_6= 49.854	α_7= 64.178
	V_{dc1}= 1.000	V_{dc2}= 1.000	V_{dc3}= 1.000	V_{dc4}= 1.000	V_{dc5}= 1.000	V_{dc6}= 0.943	V_{dc7}= 1.000

TABLE VI. VALIDATION AND COMPARISON BETWEEN ALL METHODS

Angles		**THD_{49}**	**THD_{10^6}**	**THD_{Actual}**
6 switching angles for 13 level inverter	**THD**	4.9710	6.0720	6.0721
7 switching angles for 15 level inverter	**THD**	4.3254	5.3028	5.3029
Implementing in Computer		Easy	Easy	Easy
Running Time (Second)		0.0002	1.7876	91×10^{-7}
Calculating by paper & pen		Hard	Impossible	Easy

THD_{10}^6 has teeny error. All methods can be implemented in a computer program easily. Each method is run 20 times and the least running time is selected. The comparison shows that THD_{Actual} has the least running time. A computer with the following characteristic is applied: Pentium(R) Dual-Core CPU 2.5 GHz, 2.00 GB of RAM. Also, calculating the THD_{actual} by paper & pen is easy, whereas taking several harmonics into account is hard.

V. CONCLUSION

Approximate methods are employed for calculation of the PVTHD, which only considers a limited number of low Order harmonic. In this paper, the accurate methods are presented to calculate of PVTHD for 5, 13 and15 level inverter, via three methods, Computer programming via V_{rms}, Formulation of PVTHD via THDM and Optimization of PVTHD via ICMPPSO algorithm. Because of the different values of THD between accurate and approximate methods, for a large interval of modulation index, is at least 1% and the maximum reaches to ∞, these accurate methods are recommended as a standard method to calculate of PVTHD in multilevel inverter with adjustable DC sources. When angles approaches to the 90 degrees, the different values approach to the infinite in this interval which have been shown in simulation results section. The different values in 56.07 percent of interval of modulation index, are greater than 2% that is unacceptable. But, according to the IEEE-519 standard for Harmonics, the THD value less than 5% is acceptable. The value of 2% error compared with 5%, is not acceptable in any way because has 40% error. According to these results, using of approximate method is not acceptable. The speed and accuracy calculation of accurate methods much more than approximate method and can be used in an ON-Line application. The running time in approximate method for calculation of THD till 49^{th} order (THD_{49}), is 0.0002 second but this time is 91×10^{-7} second for accurate method.

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Hadi Vadizadeh was born in Karaj, Iran, in 1987. He received the B.Sc. Degree in electrical engineering from the Sadra University in 2009. He received the M.Sc. Degree in electrical engineering from the West Tehran Branch, Islamic Azad University, Tehran, Iran in 2013, where he is currently working toward the Ph.D. degree in the power electronic Lab. He is first ranked among all B.Sc. And M.Sc. Students in the department of electrical engineering. He has joined to the elite national foundation as an elite in December 2009. He has joined to the Young Researchers Club, South Tehran Branch, Islamic Azad University, Tehran, Iran in March 2010 and currently working as a researcher at this institute. His research interest area includes power electronic, multilevel inverter and FACTS devices.

Ebrahim S. Afjei received the B.S. and M.S. degrees in Electrical Engineering from the University of Texas in 1984, 1986 respectively, and the Ph.D. degree from New Mexico State University, in 1991. He is currently a Professor and Dean of the Department of Electrical Engineering, Shahid Beheshti University G.C., Tehran, IRAN. His research interests are in the areas of switched reluctance motor drives, Numerical analysis and power electronics.

Alireza Siadatan received the B.S. degree in Electrical Engineering from the Shahid Beheshti University G.C., Tehran, IRAN in 2001, He is currently a last year Student of Ph.D. in Electrical Engineering at the Shahid Beheshti University G.C., Tehran, IRAN. He is currently a Faculty Member and Dean of Research in the Department of Electrical Engineering, Islamic Azad University (West Tehran Branch), Tehran, Iran. His research interests are in the areas of power electronics, design of switched reluctance machine, numerical analysis, renewable energy and drives.