MINIMIZATION OF THD IN CASCADE MULTILEVEL INVERTER USING WEIGHT IMPROVED PARTICLE SWARM OPTIMIZATION ALGORITHM

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ABSTRACT

Using multilevel inverter in numerous applications is commonplace. Inverters supplied from equal dc source are almost rare. Although variation in dc source affects inverter switching characteristics. Solving a nonlinear transcendental equation set describing harmonic elimination with non-equal dc sources reaches the limitation of contemporary computer algebra software tools as marked in literatures. This paper presents an optimal solution for harmonic reduction namely weight improved particle swarm optimization (WIPSO), where a set of mathematical equation describing the general output waveform for the computation of total harmonic distortion (THD) is used as the objective function and is employed to compute the optimal solution set of switching angles without knowing proper initial guess. Theoretical analysis is validated through simulations for 5, 7, 9 and 11 level cascaded multilevel inverters performed on MATLAB software. Results show a decrease in THD as level of inverter increases reflecting to approach towards a sinusoidal output voltage waveform thereby eliminating harmonics.

KEYWORDS

Multilevel Inverter, Particle Swarm Optimization (PSO), Selective Harmonic Elimination (SHE), THD, Weight Improved Particle Swarm Optimization (WIPSO)

1. INTRODUCTION

Multilevel Inverter is measured as one of the most noteworthy recent advance in industrial applications. Presently, most of their application is in the low to medium power range. Solutions that allow connection to high power grids, such as silicon-carbide (SIC) switches, are still untested and will take some time before introduction into commercial applications. Instead, research and development has focused on multilevel converters in past few years and have emerged as a new breed of power converter options for high power applications such as adjustable speed motor drives (ASD), unity power factor rectifications (PFC), active power filtering (APF), static var compensation (STATCOM), and unified power flow control (UPFC) system. Its concept is based on producing small output voltage steps, resulting in better power quality. Its advantages include better electromagnetic compatibility due to low dv/dt transitions, low operating voltage level, low switching frequency.

The well-known multilevel topologies are cascade H Bridge, neutral-point clamp (NPC) or diode-clamped and flying capacitor. The NPC which prevailed in the 1980's having found its application, but to a limited number of levels were achievable due to the unbalanced voltage issues in the capacitors, voltage clamping requirements, circuit layout, stray electromagnetic interferences(EMI) and packaging constraints. The cascaded H-bridge has drawn considerable interest since the mid-1990s, and has been used commonly due to modularized circuit layout and packaging as each level has the same structure, and there are no extra clamping diodes or voltage balancing capacitor. Also the number of output voltage levels can be easily adjusted by adding or removing the full-bridge cells.

The key issue in designing an effective multilevel inverter is to ensure that the total harmonic distortion (THD) of the output voltage waveform is within acceptable limits. In general sinusoidal pulse width modulation and space vector pulse width modulation are suggested in literatures for eliminating harmonics. Conversely both the methods do not eliminate lower order harmonics completely and in the process Selective harmonic elimination (SHE) has been reported in previous works, that involves choosing the switching angles so that specific higher order harmonics such as the 5th, 7th, 11th, and 13th are suppressed in the output voltage of the inverter, to minimize lower order harmonics & THD. The primary hold-up associated with SHE is to achieve the arithmetic solution of nonlinear transcendental equations, so obtained by Fourier theory of output voltage waveform, depicting trigonometric terms and as expected present multiple solutions. Thus this problem was overcome using conventional analytical route involving iterative procedure such as Newton-Raphson technique. This method is derivative-dependent and may end in local optima, and a judicious choice of the initial values alone can guarantee conversion. Another approach available in literatures based on conversion, in which resultant theory is applied to determine the switching angles to eliminate specific harmonics, however, it appears to be unattractive because as the number of inverter levels increases, so does the degree of the polynomials of the mathematical model which lead to numerical complexity and substantial computational burden.

A new area of optimizations, based on evolutionary algorithms, is gaining popularity such as Genetic Algorithms (GA), Ant Colony Systems (ACS), Bee Algorithms (BA) and particle swarm optimization (PSO) to combat above drawbacks. Previously reported studies depicts that these method does effectively eliminate number of specific harmonics, and the output voltage results in low total harmonic distortion.

This paper present a Heuristic algorithm namely Particle Swarm Optimization (PSO) in order to reduce the computational burden associated with the solution of the non-linear transcendental equations of the harmonic elimination problem of a cascaded H bridge inverter with non-equal dc sources. As an optimization technique, PSO is much less dependent on the start values and is randomly generated from the search space. It has the advantage of obtaining the optimal solution in short time. Problem formulation and analysis are presented, simulation for 5, 7, 9 and 11 level inverter are carried out, and so compared to obtain result, where the superiority of the algorithm is reported.

2. POWER TOPOLOGY OF CASCADE MULTILEVEL INVERTER

A relatively new converter structure, cascaded-inverters with separate dc sources (SDC's) is most important topology in the family of multilevel inverter. It avoids extra clamping diodes and voltage balancing capacitors as compared to other two topologies. It is simply a series connection of multiple H-bridge inverters which has the same configuration as a typical single-phase full-bridge inverter that can generate three level outputs $+V_{dc}$, 0, $-V_{dc.}$ Fig.1 (a) shows the basic structure of the cascaded-inverters with SDC's, shown in a single-phase configuration. To comply with the definition of other two topology, the "level" in a cascaded-inverters based converter is defined by m = 2s + 1, where *m* is the output phase voltage level and *s* is the number of dc sources. For example, an 11-level cascaded inverters based converter will have five SDC's and five full bridges as shown in Fig. 1(a).

By connecting the sufficient number of H-bridges in cascade and using proper modulation scheme, a nearly sinusoidal rather staircase output voltage waveform can be synthesized. Fig.1 (b) shows an 11-level output phase voltage waveform using five H-bridges. Thus resulting AC output voltage is synthesized by the addition of the voltages generated by different H-bridge cell & magnitude is given by $V_{ao} = V_1+V_2+V_3+V_4+V_5$. In the Fig. 1(b), θ_1, θ_2, θ_3, θ_4, & θ_5 are the switching angles for five H-bridges in each phase and $(\pi- \theta_1)$, $(\pi- \theta_2)$, $(\pi- \theta_3)$, $(\pi- \theta_4)$ & $(\pi- \theta_5)$ are corresponding supplementary angles for θ_1, θ_2, θ_3, θ_4, & θ_5 .

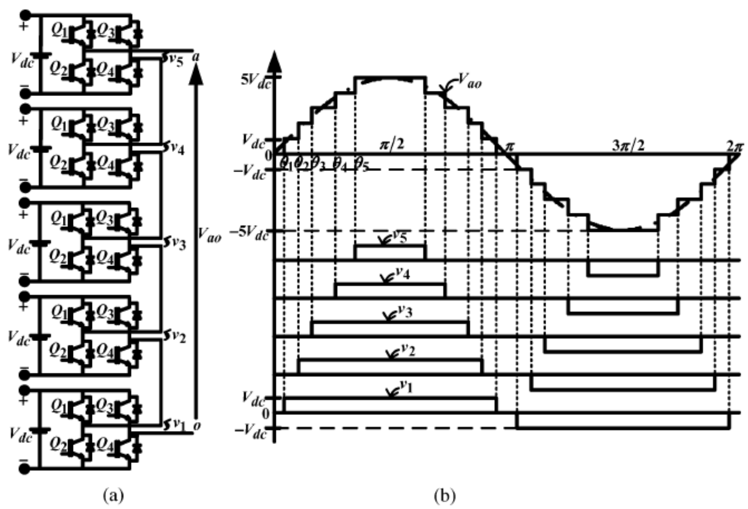

Figure 1 : (a) Topology of a single phase cascade inverter. (b) Staircase output voltage waveform

The magnitude and THD content of output voltage depends very much on these switching angles & thus need to be selected properly.

3. HARMONIC MINIMIZATION PROBLEM FORMULATION

3.1. Fourier Analysis and Expansion

In general, Fourier series analysis is used to obtain the expression for staircase output voltage of cascade multilevel inverter. Since the generalized output waveform as shown in Fig. 1 (b) is non-sinusoidal, therefore it may be expressed in Fourier series expansion in its general form as:

$$v_{\text{out}}(\theta) = A_o + \sum_{n=1}^{\infty}(A_n \cos n\theta + B_n \sin n\theta) \quad (1)$$

where

$$A_o = \frac{1}{2\pi}\int_0^{2\pi} f(t)\, dt, \quad A_n = \frac{1}{\pi}\int_0^{2\pi} f(t) \sin n\omega t\, dt,$$
$$B_n = \frac{1}{\pi}\int_0^{2\pi} f(t) \cos n\omega t\, dt \quad (2)$$

Since all inverter output voltages have no dc component or average value, therefore $A_o = 0$. Also, as the general waveform shown in Fig. 1(b) possesses an odd function or point symmetry, i.e. f (t) = -f (-t), and mirror or half- and quarter-wave symmetry i.e. f (t) = -f (t + 90°), only sinusoidal terms with odd order harmonics exit in the expansion. Then Eq. (1) is reduced to:

$$v_{\text{out}}(\theta) = \sum_{n=1,3,5,\ldots}^{\infty} B_n \sin n\theta \quad \text{...........} (3)$$

Assuming that the non-equal dc sources are known, and taking into consideration the above mentioned characteristics of the inverter waveform shown in Fig. 1(b), the Fourier series expansion of the generalized stepped output voltage waveform of the multilevel inverter with non-equal dc sources can be expressed as:

$$V(\omega t) = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{\text{dc}}}{n\pi} \times (k_1 \cos(n\theta_1) + k_2 \cos(n\theta_2) + k_3 \cos(n\theta_3) + \cdots + k_s \cos(n\theta_s)) \sin(n\omega t) \quad \text{.............} (4)$$

Where s is the number of H-bridges connected in cascade per phase, k is order of harmonic components, V_{dc} is nominal dc voltage and switching angles $\theta_1 - \theta_s$ must satisfy the following condition $\theta_1 < \theta_2 < \theta_3 < \ldots\ldots\ldots\theta_s < \frac{\pi}{2}$.

3.2. Selective Harmonic Elimination (SHE)

The main area of concern in multilevel inverter is determination of switching angles 's' for harmonic minimization. Furthermore, number of harmonic getting eliminated from the output voltage is "s-1" and set of 's' transcendental SHE equations are obtained by assigning a specific value to the fundamental component of voltage, V_1

$$V_1 = \frac{4V_{dc}}{\pi} (k_1 \cos\theta_1 + k_2 cos\theta_2) \text{ ....} (5)$$

and equating "s-1" harmonics to zero. From equation (4), the expressions for SHE equations are mentioned below:

$$k_1 \cos\theta_1 + k_2 cos\theta_2 + \ldots\ldots\ldots + K_s \cos\theta_s = (\frac{\pi}{2})M$$
$$k_1 \cos(3\theta_1) + k_2 \cos(3\theta_2) + \ldots\ldots\ldots + K_s \cos(3\theta_s) = 0$$
$$k_1 \cos(5\theta_1) + k_2 cos(5\theta_2) + \ldots\ldots\ldots + K_s \cos(5\theta_s) = 0$$
$$k_1 \cos(n\theta_1) + k_2 cos(n\theta_2) + \ldots\ldots\ldots + K_s \cos(n\theta_s) = 0$$

In above SHE equations, Modulation Index 'M' is defined as $M = \frac{V_1}{sV_{dc}}$, $0 \le M \le 1$. . The main challenge in solving above set of SHE equations is its non-linearity, as most iterative techniques suffer from convergence problems and other techniques such as elimination using resultant and GA are complicated as reported in previous literatures. Hence Weight Improved Particle Swarm optimization (WIPSO) technique is presented in following section of paper for achieving above result.

An objective function is later needed for the optimization procedure, which is selected as a measure of effectiveness for eliminating selected order of harmonics while maintaining the fundamental component at a pre-specified value. Therefore, objective function is defined as:

$$f(\theta_1, \theta_2, \ldots, \theta_s) = 100 \times \left[\left| M - \frac{|V_1|}{sV_{dc}} \right| + \left(\frac{|V_5| + |V_7| + \cdots + |V_{3s-2 \text{ or } 3s-1}|}{sV_{dc}} \right) \right] \quad \ldots\ldots (6)$$

4. PARTICLE SWARM OPTIMIZATION (PSO)

PSO is an efficient evolutionary optimization paradigm that was proposed by Kennedy and Eberhart in 1995. It is developed from swarm intelligence and is a population-based robust stochastic optimization technique intends to graphically simulate the graceful and unpredictable choreography of a bird folk i.e. is inspired by the social behaviour of creatures such as fish schooling, bird-flocking and herds of animals.

The system is initialized with a population of random solutions & searches for optima by updating generations. The individual in the population are called particles. It tries to search the best position by flying in a multidimensional space until an unchanging position of the fittest particle is encountered.

In general, each particle is determined by two vectors operator in D-dimensional search space: the position vector $X_i = [x_{i1}, x_{i2} . . . x_{iD}]$ and the velocity vector $V_i = [v_{i1}, v_{i2}, . . . , v_{iD}]$ respectively. Instead of using more traditional genetic operators, it modifies its movement according to its own experience and its neighbouring particle experience. This implies that each particle has memory, which allows it to remember the best position on the feasible search space that has ever visited. This value is commonly called Pbest. Another best value that is tracked by the particle swarm optimizer is the best value obtained so far by any particle in the neighbourhood of the particle. This location is commonly called Gbest. On the basis of the value of the objective function as formulated above, the best previous position of a particle is recorded and represented as $Pbest_i= [p_{i1}, p_{i2} . . . p_{iD}]$. If the g^{th} particle is the best among all particles in the group so far, it is represented as $Gbest= Pbest_g= [pg_1, pg_2 . . . pg_D]$. The particle tries to modify its position using the current velocity and the distance from Pbest and Gbest. In addition, both the values are updated after every iteration until convergence is obtained. The modified velocity and position of each particle for fitness evaluation in the next iteration are calculated using the following equations:

$$v_{id}^{k+1} = w \times v_{id}^{k} + c_1 \times rand_1 \times (Pbest_{id} - x_{id}^{k}) + c_2 \times rand_2 \times (Gbest_{gd} - x_{id}^{k}) \quad \ldots\ldots\ldots\ldots (7)$$

$$x_{id}^{k+1} = x_{id}^{k} + v_{id}^{k+1} \quad \ldots\ldots\ldots\ldots (8)$$

where, V_{id}^k is current velocity of the particle, x_{id}^k is current position of the particle, ω is inertia weight, c_1 is cognition acceleration coefficient, c_2 is social acceleration coefficient, $Pbest_{id}$ is best position of particle, $Gbest_{gd}$ is global best position among the group of particles and $rand_1$ and $rand_2$ are uniformly distributed random numbers in the range [0 to 1]. 'g' is the index of the best particle in the swarm, k is discrete time index, d = (1, 2….n) represents the dimension and i = (1, 2… s) represent the particle index.

The basic concept behind the PSO technique consists of change in the velocity of each particle toward its Pbest and Gbest positions at each time step. The concept of a moving particle is illustrated in Fig.2.

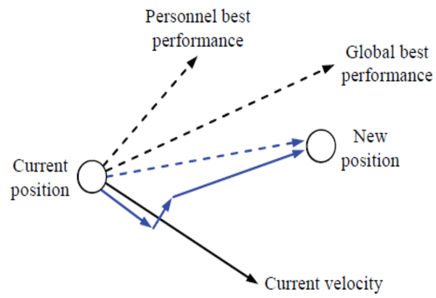

Figure 1 : Concept of modification of searching points

The modified velocity equation (7) as marked above, also very well depicts the pictorial concept of fig. 2 in which first term indicate inertia or habit, where each particle continuously moved in the direction it had previously moved, second term reflect the memory where each particle is attracted to the best point in its trajectory P and third term represent a cooperation or information exchange, in which each particle is attracted to the best point found by all particles G. Hence it is clearly understood that values of c_1 and c_2 allow the particle to tune the individual & social terms respectively towards the better result.

4.1. Weight Improved Particle Swarm Optimization (WIPSO)

There is a large impact of initial velocity in the balancing of exploration and exploitation process of swarm but as the training progresses, the influence of the past velocity becomes smaller. Thus this balance is achieved by incorporating Inertia weight 'w' in the classical version of PSO algorithm to portray as Weight Improved Particle Swarm Optimization (WIPSO) thereby increasing its capabilities. For early stages of search, a relatively large inertia is used to enhance the global exploration and when reaching the last stages, the inertia is reduced for better local exploitation.

To certify the effectiveness of the algorithm in minimizing THD, experiments have been carried out for 2 types of inertia weight strategies over optimization problem for the proposed work, namely linearly decreasing inertia weight (LDIW) and Sigmoid decreasing inertia weight (SDIW) described using mathematical equations [5] and [6] respectively as:

1.	Sigmoid Decreasing Inertia Weight	$w_k = \frac{(w_{start} - w_{end})}{(1 + e^{-u*(k-n*gen)})} + w_{end}$ $u = 10^{(log(gen)-2)}$
2.	Linear Decreasing Inertia Weight	$w_k = w_{max} - \frac{w_{max} - w_{min}}{iter_{max}} \times k$

The value of w is allowed to decrease linearly with iteration from w_{max} to w_{min} as w_{max} = 0.9 and w_{min}= 0.4 taken from literature. $iter_{max}$ is the maximum number of iteration, k is current iteration throughout the pseudo code. Furthermore, u is the constant to adjust sharpness and n is used to set partition of sigmoid function.

4.2. Implementation of PSO Algorithm

The aim is to minimize cost function f $(\theta_{i1}, \theta_{i2}, \dots \dots \theta_{is})$ as expressed in equation (6), for calculation of optimal switching angles subject to the constraint $\theta_1 < \theta_2 < \theta_3 < \dots \dots \dots \theta_s < \frac{\pi}{2}$. Let

$\theta_i = [\theta_{i1}, \theta_{i2}, \dots\dots \theta_{is}]$be a trial vector representing the i_{th} particle of the swarm to be evolved. The elements of θ_i are the solutions of the harmonic minimization problem, and the d_{th} element of that is corresponding to the d_{th} switching angle of the inverter. The step-by-step procedure to solve the SHE problem with non-equal dc sources is as follows.

1. Enter the data for the system: Input the value of required parameters for the algorithm such as population size M, maximum iteration number $iter_{max}$, acceleration constant, start & end values of inertia weight etc., and set the iteration counter k = 1.
2. Create the initial position and velocity matrix of particle: Each particle position is randomly initialized between 0 and $\frac{\pi}{2}$ and particle velocity vector within $-V_{max}$ and V_{max}.
3. Compute the objective function: Every particle in the population is assessed using objective function and so is obtained using equation (6) by applying required SHE set. The switching angles $[\theta_{i1}, \theta_{i2}, \dots\dots \theta_{is}]$ thus can be calculated up to the 3s – 2th order while s is odd and up to the 3s-1th order when s is even by minimizing the cost function in order to achieve the harmonic profile.
4. Revise the personal and global best position: The fitness value obtained above is set initially as Pbest value of the particle and are compared amongst the other for the best replacement as per swarm size. In addition, if the Pbest of the particles is better than the global best, then global best Pg are replaced with Pbest.
5. Determine the inertia weights using the data available from the previous studies as presented in the paper.
6. All particles in the population are revised by the velocity and position matrix rules (7) and (8), respectively. Also the matrix so obtained is verified for its correctness within given constraints established in step (2).
7. Termination criterion: If the iteration counter k reaches $iter_{max}$, stop; else, increase the iteration counter k = k + 1 and go back to step (3).
8. Plot the result to obtain the output voltage waveform along with performance characteristics Graph.

5. COMPUTATIONAL RESULT

The generalized transcendental equations and optimal switching angles of multilevel inverter are solved using the described PSO algorithm. The proposed work is implemented on 5, 7, 9 and 11 level cascade inverter accomplished in the MATLAB programming environment. The nominal dc voltage is considered to be 100v and the K_i values are listed in Table 1.

Table 1: Typical values of Ki used in calculation

K_1	K_2	K_3	K_4	K_5
1.08	0.89	0.9	0.86	0.8

The main objective here is to minimize the THD of generated output voltage waveform by determining switching angle. For objective function of 5, 7, 9 and 11 level inverter respectively, six different swarm sizes are tested. They are: 5, 10, 15, 20, 25, and 30. The maximum number of iterations is set as 100 and 150 corresponding to the dimension respectively. Also to avoid the effect of choice of initial population, 30 simulation trails are taken for every swarm size and amongst it, minimal optimum function set is considered. The value of acceleration parameters c_1 and c_2 are taken equal to 2. A sigmoid and linearly decreasing inertia weight is used as comparison in all the four case study for each level and is taken at 0.4 until 0.9. Furthermore for best partition of sigmoid function, constant n is taken as 0.5.The computational results so gained are presented in following case study.

5.1. Case 1: 5- Level Inverter

It includes the series connection of two H-bridge inverters, values of which are unequal. Taken from previous research, let's consider the source for first level to be 108% of nominal dc voltage (k_1 = 1.08) and 89% for the second level (k_2 = 0.89). The result so obtained, amongst 30 trials of each swarm size, of switching angles on two weight strategies based on minimization of objective function are shown in Table 8 and Table 9.

5.2. Case 2: 7- Level Inverter

It includes the series connection of three H-bridge inverters, values of which are unequal. Taken from previous research, let's consider the source for first level to be 108% of nominal dc voltage (k_1 = 1.08), 89% for the second level (k_2 = 0.89) and 90% for the third level (k_3 = 0.9). The result so obtained, amongst 30 trials of each swarm size, of switching angles on two weight strategies based on minimization of objective function are shown in Table 8 and Table 9.

5.3. Case 3: 9- Level Inverter

It includes the series connection of four H-bridge inverters, values of which are unequal. Taken from previous research, let's consider the source for first level to be 108% of nominal dc voltage (k_1 = 1.08), 89% for the second level (k_2 = 0.89), 90% for the third level (k_3 = 0.9) and 86% for the fourth level. The result so obtained, amongst 30 trials of each swarm size, of switching angles on two weight strategies based on minimization of objective function are shown in Table 8 and Table 9.

Table 2: Optimal result with different population size and iteration

5 - LEVEL								
TECHNIQUE USED : LDIW								
POP. SIZE	100 ITERATION				150 ITERATION			
	Switching Angles in radian		Objective Function	THD (%)	Switching Angles in radian		Objective Function	THD (%)
	Θ_1	Θ_2			Θ_1	Θ_2		
5	0.1897	0.7854	9.3570E-13	2.3873E-04	0.1897	0.7854	1.5055E-13	9.9565E-07
10	0.1897	0.7854	4.9991E-12	4.6466E-10	0.1897	0.7854	1.7764E-14	12.5099
15	0.1897	0.7854	5.5487E-12	6.674	0.1897	0.7854	3.9080E-14	10.999
20	0.1897	0.7854	2.4651E-11	1.0370E-06	0.1897	0.7854	2.1538E-14	1.6393E-06
25	0.1897	0.7854	9.6156E-12	3.8176E-06	0.1897	0.7854	1.8430E-14	18.9741
30	0.1897	0.7854	3.2434E-12	2.7095E-06	0.1897	0.7854	2.3981E-14	1.4931E-05

Table 3: Optimal result with different population size and iteration

5 - LEVEL								
TECHNIQUE USED : SDIW								
POP. SIZE	**100 ITERATION**				**150 ITERATION**			
	Switching Angles in radian		**Objective Function**	**THD (%)**	**Switching Angles in radian**		**Objective Function**	**THD (%)**
	Θ_1	**Θ_2**			**Θ_1**	**Θ_2**		
5	0.1897	0.7854	1.89E-12	1.1567	0.1897	0.7854	2.4425E-15	8.0205E-08
10	0.1897	0.7854	6.5947E-13	2.0028E-06	0.1897	0.7854	2.2204E-16	1.3097E-07
15	0.1897	0.7854	6.9722E-13	6.7366E-08	0.1897	0.7854	2.2204E-16	1.1610E-08
20	0.1897	0.7854	3.2063E-13	4.5266E-05	0.1897	0.7854	0	1.0342E-06
25	0.1897	0.7854	5.0626E-14	7.2775E-07	0.1897	0.7854	0	16.3983
30	0.1897	0.7854	1.4899E-13	6.2890E-05	0.1897	0.7854	0	7.0624E-09

Table 4: Optimal result with different population size and iteration

7 - LEVEL										
TECHNIQUE USED : LDIW										
POP. SIZE	**100 ITERATION**					**150 ITERATION**				
	Switching Angles in radian			**Objective Function**	**THD (%)**	**Switching Angles in radian**			**Objective Function**	**THD (%)**
	Θ_1	**Θ_2**	**Θ_3**			**Θ_1**	**Θ_2**	**Θ_3**		
5	0.212	0.524	0.989	0.006	8.646	0.215	0.546	1.013	0.001	11.831
10	0.216	0.524	0.996	0.003	9.227	0.245	0.646	1.066	0.002	7.358
15	0.216	0.524	1.000	0.002	8.833	0.214	0.524	1.003	0.003	7.066
20	0.241	0.635	1.061	0.001	5.891	0.215	0.524	1.000	0.001	8.204
25	0.212	0.524	0.998	0.001	9.207	0.216	0.524	1.001	0.002	6.794
30	0.210	0.524	1.000	0.003	4.634	0.213	0.524	0.998	0.000	8.605

Table 5: Optimal result with different population size and iteration

7 – LEVEL										
TECHNIQUE USED : SDIW										
POP. SIZE	**100 ITERATION**					**150 ITERATION**				
	Switching Angles in radian			**Objective Function**	**THD (%)**	**Switching Angles in radian**			**Objective Function**	**THD (%)**
	Θ_1	**Θ_2**	**Θ_3**			**Θ_1**	**Θ_2**	**Θ_3**		
5	0.217	0.524	1.004	0.003	4.694	0.215	0.546	1.013	0.001	11.831
10	0.216	0.524	0.993	0.003	6.209	0.212	0.524	1.004	0.004	4.313
15	0.211	0.524	0.997	0.001	3.694	0.214	0.524	0.999	0.001	1.335
20	0.227	0.603	1.048	0.003	10.241	0.211	0.524	0.998	0.002	10.071
25	0.213	0.524	1.000	0.001	7.724	0.212	0.524	1.000	0.001	1.335
30	0.213	0.524	1.000	0.001	0.084	0.214	0.524	1.000	0.001	1.335

Table 6: Optimal result with different population size and iteration

9 - LEVEL												
TECHNIQUE USED : LDIW												
POP. SIZE	100 ITERATION						150 ITERATION					
	Switching Angles in radian				Objective Function	THD (%)	Switching Angles in radian				Objective Function	THD (%)
	Θ_1	Θ_2	Θ_3	Θ_4			Θ_1	Θ_2	Θ_3	Θ_4		
5	0.058	0.421	0.705	1.507	0.013	7.737	0.198	0.437	0.739	1.074	0.015	11.692
10	0.189	0.468	0.776	1.103	0.008	6.426	0.071	0.461	0.747	1.491	0.006	15.669
15	0.187	0.393	0.692	1.048	0.014	5.583	0.197	0.454	0.766	1.136	0.013	7.706
20	0.058	0.421	0.705	1.507	0.013	7.201	0.172	0.393	0.701	1.068	0.006	4.818
25	0.175	0.419	0.703	1.089	0.016	4.248	0.180	0.421	0.729	1.086	0.002	5.286
30	0.068	0.420	0.717	1.488	0.012	1.043	0.183	0.430	0.732	1.100	0.008	8.005

Table 7: Optimal result with different population size and iteration

9 - LEVEL												
TECHNIQUE USED : SDIW												
POP. SIZE	100 ITERATION						150 ITERATION					
	Switching Angles in radian				Objective Function	THD (%)	Switching Angles in radian				Objective Function	THD (%)
	Θ_1	Θ_2	Θ_3	Θ_4			Θ_1	Θ_2	Θ_3	Θ_4		
5	0.058	0.421	0.705	1.507	0.013	7.737	0.198	0.393	0.739	1.074	0.020	11.633
10	0.189	0.468	0.776	1.103	0.008	6.426	0.181	0.393	0.682	1.059	0.009	0.604
15	0.168	0.393	0.692	1.048	0.010	5.623	0.197	0.454	0.766	1.136	0.013	7.706
20	0.183	0.393	0.682	1.057	0.009	6.715	0.170	0.393	0.677	1.058	0.009	2.516
25	0.176	0.393	0.680	1.049	0.007	6.652	0.180	0.393	0.701	1.077	0.005	0.323
30	0.169	0.393	0.673	1.045	0.011	8.047	0.177	0.393	0.691	1.062	0.004	8.800

5.4. Case 4: 11- Level Inverter

It includes the series connection of five H-bridge inverters, values of which are unequal. Taken from previous research, let's consider the source for first level to be 108% of nominal dc voltage (k_1 = 1.08), 89% for the second level (k_2 = 0.89), 90% for the third level (k_3 = 0.9), 86% for the fourth level and 80% for the five level (k_5 = 0.8). The result so obtained, amongst 30 trials of each swarm size, of switching angles on two weight strategies based on minimization of objective function are shown in Table 8 and Table 9.

Table 8: Optimal result with different population size and iteration

11 - LEVEL														
TECHNIQUE USED : LDIW														
POP. SIZE	100 ITERATION							150 ITERATION						
	Switching Angles in radian					Objective Function	THD (%)	Switching Angles in radian					Objective Function	THD (%)
	Θ_1	Θ_2	Θ_3	Θ_4	Θ_5			Θ_1	Θ_2	Θ_3	Θ_4	Θ_5		
5	0.077	0.314	0.393	0.637	0.984	0.004	4.350	0.085	0.314	0.393	0.655	0.998	0.003	4.406
10	0.084	0.336	0.393	0.681	1.016	0.001	3.989	0.081	0.314	0.393	0.648	0.993	0.002	0.120
15	0.072	0.314	0.393	0.628	0.970	0.005	3.606	0.081	0.314	0.393	0.648	0.994	0.002	2.776
20	0.088	0.314	0.393	0.652	1.001	0.002	6.095	0.085	0.314	0.393	0.655	0.998	0.003	4.865
25	0.080	0.314	0.393	0.641	0.988	0.003	4.492	0.088	0.314	0.393	0.655	1.004	0.002	2.762
30	0.088	0.314	0.393	0.655	1.001	0.003	5.201	0.089	0.314	0.393	0.655	1.005	0.002	2.318

Table 9: Optimal result with different population size and iteration

11 - LEVEL															
TECHNIQUE USED : SDIW															
POP. SIZE	100 ITERATION							150 ITERATION							
	Switching Angles in radian					Objective Function	THD (%)	Switching Angles in radian					Objective Function	THD (%)
	Θ_1	Θ_2	Θ_3	Θ_4	Θ_5			Θ_1	Θ_2	Θ_3	Θ_4	Θ_5		
5	0.116	0.318	0.476	0.778	1.072	0.012	0.821	0.129	0.314	0.492	0.723	1.031	0.019	6.512
10	0.096	0.314	0.393	0.686	1.013	0.015	4.265	0.102	0.314	0.401	0.678	1.040	0.011	3.201
15	0.163	0.314	0.393	0.614	1.009	0.008	5.271	0.120	0.314	0.393	0.643	1.030	0.015	3.580
20	0.105	0.314	0.393	0.651	1.007	0.013	3.695	0.106	0.314	0.393	0.663	1.026	0.010	6.104
25	0.109	0.314	0.402	0.687	1.021	0.009	9.969	0.117	0.314	0.429	0.708	1.037	0.008	4.027
30	0.096	0.314	0.402	0.674	1.029	0.009	4.101	0.112	0.314	0.431	0.700	1.045	0.007	4.759

5.5. Performance Index

In order to designate the worth and effectiveness of the presented paradigm, a quality factor is chosen as a performance index called Total Harmonic Distortion (THD). It is defined as the total amount of harmonics relative to the fundamental, and can be calculated using Eq. (9) as revealed below. It is very useful factor to assess the performance of the inverter, and therefore it is considered in this work.

$$THD = \sqrt{\sum_{n=5,7,11,\ldots}^{49} V_n^2} \Big/ V_1. \quad \text{............ (9)}$$

5.6. Result Analysis

This paper present a comparative study on 2 strategies to set inertia weight in particle swarm optimization of 5, 7, 9 and 11 level inverter as tabulated in Table 2 to Table 9. Referring to these tabulated results of various levels, there is only one set of solution among the six tested swarm size, based on minimization of objective function to achieve the result nearly and approximately to zero thereby eliminating harmonics. Like example, for five-level inverter in case of LDIW, it is clear from table 2 that population size 10 is giving best value of objective function i.e. 1.7764E-14 with 12.5% THD at 150 nos. of iteration while in case of SDIW, population size 25 is giving best objective function i.e. 0.00 with 16.4% THD at 150 nos. of iteration as observed from table 3. Similarly other levels are also summarized. Hence comparison of optimal objective function, THD and switching angles for 5, 7, 9 and 11 level multilevel inverter using Linear decreasing Particle Swarm Optimization (LDPSO) and Sigmoid decreasing Particle swarm optimization (SDPSO) are reflected in Table 10 and Table 11.

Table 10: Optimal objective function, THD and switching angles for 5, 7, 9 and 11 level inverter using LDPSO

Level (s)	LDIW_PSO						
	Objective Function	THD (%)	Switching angles in Radian				
			Θ_1	Θ_2	Θ_3	Θ_4	Θ_5
5	0.000	12.5	0.1897	0.7854	……	……	……
7	0.000	8.605	0.213	0.524	0.998	……	……
9	0.002	5.286	0.180	0.421	0.729	1.086	……
11	0.001	3.989	0.084	0.336	0.393	0.681	1.016

Table 11: Optimal objective function, THD and switching angles for 5, 7, 9 and 11 level inverter using SDPSO

Level (s)	SDIW_PSO						
	Objective Function	THD (%)	Switching angles in Radian				
			Θ_1	Θ_2	Θ_3	Θ_4	Θ_5
5	0.000	16.4	0.1897	0.7854	……	……	……
7	0.001	0.084	0.213	0.524	1.000	……	……
9	0.004	8.800	0.177	0.393	0.691	1.062	……
11	0.007	4.759	0.112	0.314	0.431	0.700	1.045

It is evident from table 10 that as the number of level increases in the output voltage of inverter the value of THD gets decrease to 3.4%. However it is not the case in Table 11, the value of THD is uneven when number of level is getting increased. This concludes that Linear decreasing inertia weight is the best strategy for best accuracy and convergence of the problem.

6. CONCLUSION

A PSO optimization technique is proposed to minimize the overall THD of the output voltage of a multilevel inverter. With the help of the developed algorithm, the switching angles are computed from the non-linear equations characterizing the SHE problem. The algorithm is easy to implement as it requires few parameters and no evolution intermediate operators. It also reduces both the computational burden and running time, and ensures the accuracy and quality of the calculated angles. It is found to be superior to conventional techniques that fail to converge if higher levels with non-equal dc sources are sought. In order to prove the feasibility of the proposed algorithm, it is applied to different study cases regarding the number of inverter levels and targeted harmonics to be eliminated and THD was taken as a performance index to examine the success of the solution.

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