SELECTIVE HARMONIC MINIMIZATION IN ASYMMETRIC CASCADED MULTILEVEL INVERTERS USING PSO & BEE ALGORITHMS

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Abstract

Multilevel Inverters achieved the desired output voltage by suitable combination of low dc variable voltages at the input side. The undesirable lower order harmonics of stepped voltage waveform can be eliminated and also the fundamental output voltage can be controlled by Selective harmonic Elimination (SHE) Method. In this method, the commutation is provided for semiconductor switches on fundamental output voltage at predetermined angles, which are optimized by soft computing technique i.e. Particle Swarm Optimization (PSO) algorithm and Bee algorithm. This paper shows PSO and Bee algorithm result to achieve the desired Fundamental output voltage and eliminate the low order harmonic for entire range of dc input voltage sources variation for 7th & 9th level cascaded inverter for three phase to eliminate 5th& 7th harmonics and 5th, 7th& 11th harmonics respectively.

Index Terms—*H-bridge Multilevel Inverter, PSO, Bee algorithm,SHE method, THD*

I. INTRODUCTION

Multilevel Inverters had been introduced and are being developed to fulfil the demand for high-voltage high-power applications, where it is impossible to connect a power semiconductor switch to a high-voltage network directly [1]. There are many applications for multilevel inverter, such as flexible AC transmission system (FACTs) equipment, high voltage direct current lines, and electrical drives [2]. In multilevel inverter, the desired output voltage is achieved by suitable combination of multiple low dc voltage sources used at the input side. As the number of dc sources is increased, the output voltage becomes closer to a pure sinusoidal waveform. Nowadays, there exist three commercial topologies of multilevel voltage source inverters; neutral point clamped (NPC), cascaded H-bridge (CHB), and flying capacitors (FCs). Among these inverter topologies, cascaded multilevel inverter reaches the higher output voltage and power levels (13.8 kV, 30 MVA) and the higher reliability due to its modular topology [3]. They can generate output voltages with extremely low distortion and lower dv/dt. They operate at low voltage levels and also at low switching frequency so that the switching losses are reduced. The main problem in designing an effective multilevel inverter is to ensure that the total harmonic distortion (THD) of the output voltage waveform is within acceptable limits. According to IEEE 519, the amount of THD should be lower than 5% [4]. Multilevel inverters produce odd harmonics itself due tohalf wave or quarter wave stepped output voltage waveform. Hence, for eliminating the low order harmonics from the output voltage, control of switching angles is the main task.

In order to generate symmetrical sinusoidal waveform in output of multilevel Inverter, odd harmonics are eliminated by selective Harmonics Elimination (SHE) Method for the wide range of dc voltage sources variation and high order harmonics are eliminated using low pass filter economically. In SHE method, the generalized stepped output voltage waveform is converted into mathematical expression using Fourier series expansion and taking into consideration the values of pre-specified desired fundamental component of output voltage and low order harmonic terms are taken to be zero. These nonlinear and complex equations are solved by using various soft computing methods such as fuzzy controller[5], Particle swarm optimization (PSO)[4], Ant colony optimization[6], Artificial neural networks[7], Genetic algorithm and bee algorithm[2] etc., which deals with imprecision, uncertainty, partial truth and approximation to achieve tractability, robustness andlow cost solution. By Applying PSO algorithm and Bee algorithm, the values of switching angles are obtained for a predefined variation in DC voltage sources.

The PSO algorithm has been used tocalculate the switching angles in real time; however, their approach was not extended for unequal dc sources [4]. Fuzzy logic controller used as alternate approach to determine the optimum switching angles for varying dc voltage sources with 10% variation [5]. Both the papers were reduced the low order harmonics in single phase multilevel inverters. Artificial neural networks (ANNs) approach for modulation of 11-level cascaded multilevel inverter using selective harmonics elimination proposed in paper [7]. This method used genetic algorithm to obtain switching angle for varying dc input voltage sources. A new approach i.e. Bee optimization method, which has higher precision and probability of convergence than the genetic algorithm, for solving the objective function for 7-level cascaded inverters [2].

II. CASCADED H-BRIDGE MULTILEVEL INVERTER

The cascaded H-bridge multilevel inverter consists of a series of Single-phase full-bridge (H-bridge) inverter units, as shown in Fig.1. It is supplied from several separate dcsources (SDCSs), which may be obtained from batteries, solar cells, or ultra-capacitors. Each SDCS is connected to a single-phase H-bridge inverter and can generate three different voltage outputs, $+V_{dc}$, 0 and $-V_{dc}$. The ac outputs of the modular H-bridge inverters are connected in series such that the synthesized voltage waveform is the sum of all of the individual inverter outputs by using different combinations of the four switches Q1, Q2, Q3, and Q4. All semiconductor devices of the H-bridges are only switching at the fundamental frequency. Three-phase version of this circuit is also available by adding another two phases and connecting their neutral point together.

III. SELECTIVE HARMONIC ELIMINATION METHOD

Generalized quarter wave or half wave Stepped output voltage of Multilevel Inverters synthesized by a (2s+1)-level inverter, where s is the number of switching angles shown in Fig.2.

Using Fourier series expansion, the output voltage waveformcan be expressed as follows:

$$v_o(wt) = \sum_{n=1,3,5\ldots}^{\infty} \frac{4Vdc}{n\pi}(\mathrm{V1}.\cos(\mathrm{n}\theta_1) + \mathrm{V2}.\cos(\mathrm{n}\theta_2) + \ldots + \mathrm{Vs}.\cos(\mathrm{n}\theta_s)).\sin(\mathrm{nwt})$$

Where $V_s.V_{dc}$ is the voltage value of s-th voltage source and

$$0 \le \theta_1 < \theta_2 < \cdots < \theta_s \le \frac{\pi}{2}$$

According to the following equations, the switching angles based on SHE method can be obtained by assuming a specified value to fundamental component and other harmonics term are taken to be zero.

$$(\mathrm{V1}.\cos(\theta_1) + \mathrm{V2}.\cos(\theta_2) + \cdots + \mathrm{Vs}.\cos(\theta_s)) = \frac{Vf.\,\pi}{4Vdc}$$
$$(\mathrm{V1}.\cos(3\theta_1) + \mathrm{V2}.\cos(3\theta_2) + \cdots + \mathrm{Vs}.\cos(3\theta_s)) = 0$$
$$(\mathrm{V1}.\cos(5\theta_1) + \mathrm{V2}.\cos(5\theta_2) + \cdots + \mathrm{Vs}.\cos(5\theta_s)) = 0$$

Where V_f is the amplitude of the fundamental component.

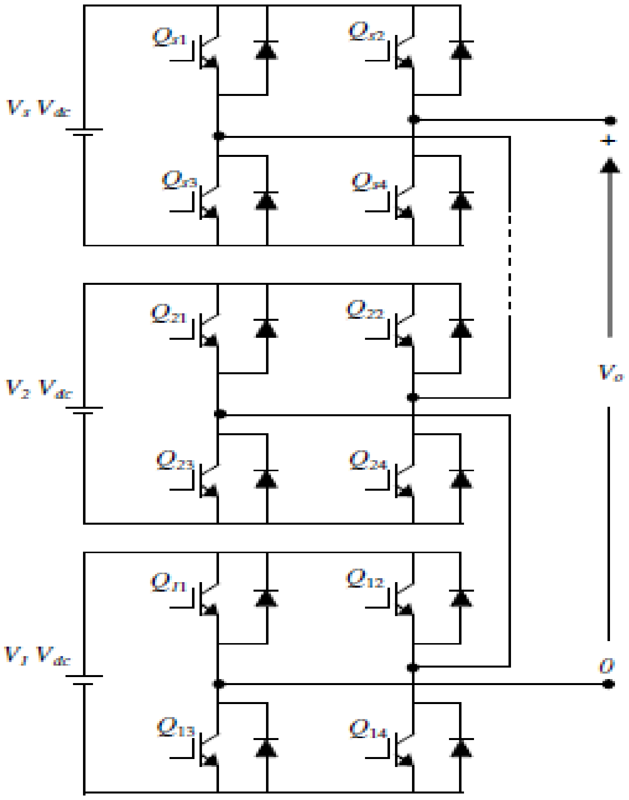

Fig. 1. Single-phase structure of a multilevel cascaded H-bridge inverter.

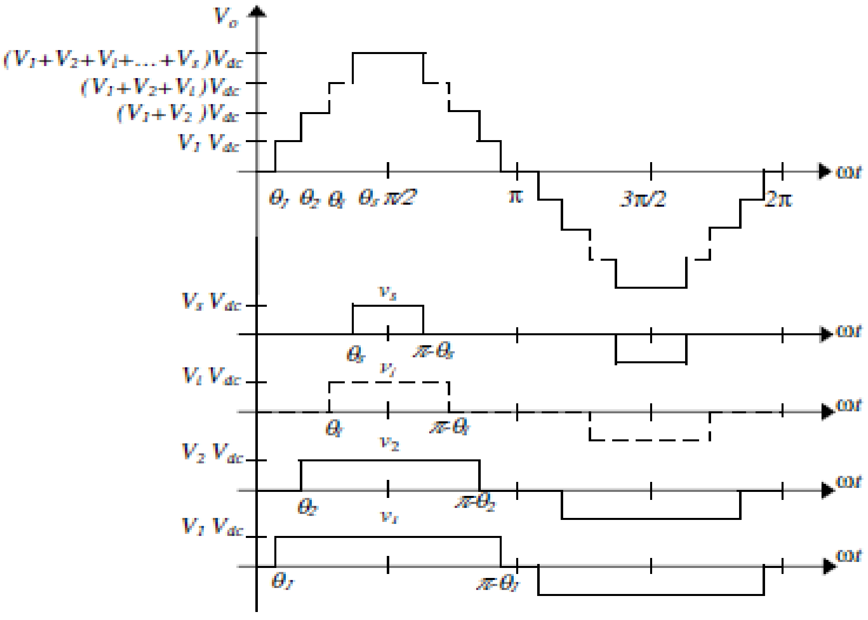

Fig. 2. Generalized output waveform of a cascaded multilevel inverter.

IV. PROBLEM FORMULATION

- **For three Phase 9-level cascaded Multilevel Inverters**

Objective function:

$$f(\theta_{1,}\theta_{2,}\theta_{3,}\theta_4) = \left[\mathrm{V1}.\cos(\theta_1) + \mathrm{V2}.\cos(\theta_2) + \mathrm{V3}.\cos(\theta_3) + \mathrm{V4}.\cos(\theta_4) - \frac{Vf.\ \pi}{4Vdc}\right]^2 + [\mathrm{V1}.\cos(5\theta_1) + \mathrm{V2}.\cos(5\theta_2) + \mathrm{V3}.\cos(5\theta_3) + \mathrm{V4}.\cos(5\theta_4)]^2 + [\mathrm{V1}.\cos(7\theta_1) + \mathrm{V2}.\cos(7\theta_2) + \mathrm{V3}.\cos(7\theta_3) + \mathrm{V4}.\cos(7\theta_4)]^2 + [\mathrm{V1}.\cos(11\theta_1) + \mathrm{V2}.\cos(11\theta_2) + \mathrm{V3}.\cos(11\theta_3) + \mathrm{V4}.\cos(11\theta_4)]^2$$

Inequality constraint: $0 \le \theta_1 < \theta_2 < \theta_3 < \theta_4 \le \frac{\pi}{2}$

- **For three phase 7-level cascaded Multilevel Inverters**

Objective function:

$$f(\theta_{1,}\theta_{2,}\theta_3) = \left[\mathrm{V1}.\cos(\theta_1) + \mathrm{V2}.\cos(\theta_2) + \mathrm{V3}.\cos(\theta_3) - \frac{Vf.\ \pi}{4Vdc}\right]^2 + [\mathrm{V1}.\cos(5\theta_1) + \mathrm{V2}.\cos(5\theta_2) + \mathrm{V3}.\cos(5\theta_3)]^2 + [\mathrm{V1}.\cos(7\theta_1) + \mathrm{V2}.\cos(7\theta_2) + \mathrm{V3}.\cos(7\theta_3)]^2$$

Inequality Constraint: $0 \le \theta_1 < \theta_2 < \theta_3 \le \frac{\pi}{2}$

V. PROPOSED METHODOLOGY

A. Particle Swarm Optimization (PSO)

Particle swarm optimization (PSO) is a population based stochastic optimization technique developed by Dr. Eberhart and Dr. Kennedy in 1995, inspired by social behaviour of birdflocking or fish schooling [8].

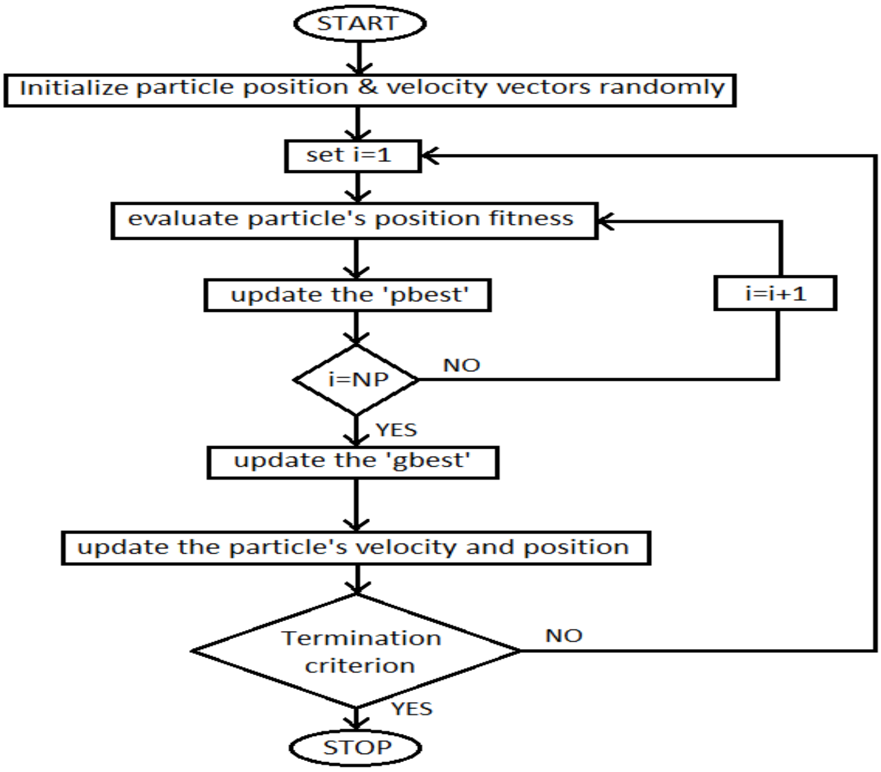

Fig.3 Flowchart of particle swarm optimization (PSO)

PSO shares many similarities with evolutionary computation techniques such as genetic algorithms (GA). The system is initialized with a population of random solutions and research for optima by updating the generations. However, unlike GA, PSO does not have evolution operators such as crossbreeding (crossover) and mutation. In PSO, potential solutions, called particles, fly through the problem space by following the current optimal particles. Compared to GA, the benefits of PSO are that PSO is easy to implement and there are few parameters to adjust. PSO has been successfully applied in many fields i.e. optimization, artificial neural network formation, fuzzy system control, and other areas where GA can be applied. PSO is initialized with a group of random particles (solutions) then search for optima by updating the generations. In each iteration, each particle is updated by following two “Best” values. The first is the best solution (fitness) has reached so far. This value is called pBest. Another “better” the value that is followed by the particle swarm optimizer is the best value, obtained so far by any particle in the population. This best value is a global best called gBest. When a particle takes part of the population as its topological neighbours, the best value is a local best and is called lBest.

After finding the two best values, the particle updates its velocity and positions with following equation (a) and (b).[9]

$$v = w * v + c_1 * rand * (pBest - p) + c_2 * rand * (gBest - p) \qquad (a)$$

$$p = p + v \qquad (b)$$

v is the particle velocity, w is Inertia weight factor, *p* is the current particle (solution). *pBest* and *gBest* are best position of the particle and swarm respectively, rand is a random number between (0,1), c1 &c2 are accelerating factors, usually c_1 = c_2= 2.

B. Bee Algorithm

The Bee algorithm is an optimization algorithm based on the natural foraging behaviour of honeybees to find the optimal solution.

A bee colony consists of three kinds of bees: employed bees, on-looker bees, and scout bees. Employed bees carry information about place and amount of nectar in a particular food source. They transfer the information to on-looker bees with dance in the hive. The time of dance determines the amount of nectar in a food source. An on-looker chooses a food source based on the amount of nectar in a food source. A good food source attracts more on-looker bees to itself. Scout bees seek in search space and find new food sources. Scout bees control the exploring process, while employed and on-looker bees play an exploiting role.

The basic flowchart of BA is shown in Fig. 4. In step 1, random initial food sources are generated. The number of initial food sources is half of the bee colony. In step 2, employed bees are sent to the food sources to determine the amount of nectar and calculate its fitness. For each food source, there is only one employed bee. So, the number of food sources is equal to the number of employed bees. In addition, the employed bees modify the solutions, saved in memory, by searching in the neighbourhood of its food source. The employed bees save the new solution if its fitness is better than the older one. Employed bees go back to the hive and share the solutions with the onlooker bees. In step 3, on-looker bees, which are another half of the colony, select the best food sources using a probability-based selection process. Food sources with more nectar attract more on-looker bees. On-looker bees are sent to the selected food sources. The on-looker bees improve the chosen solutions and calculate its fitness. Similar to employed bees, the on-looker bees save a new solution if its fitness is better than an older solution. In step 4, the food sources that are not improved for a number of iterations are abandoned. So, the employed bee is sent to find new food sources as a scout bee. The abandoned food source is replaced by the new food source. Finally, in step 5, the best food source is memorized. The maximum number of iterations is set as a termination criterion which is checked at the end of iteration. If it is not met, the algorithm returns to step 2 for the next iteration.

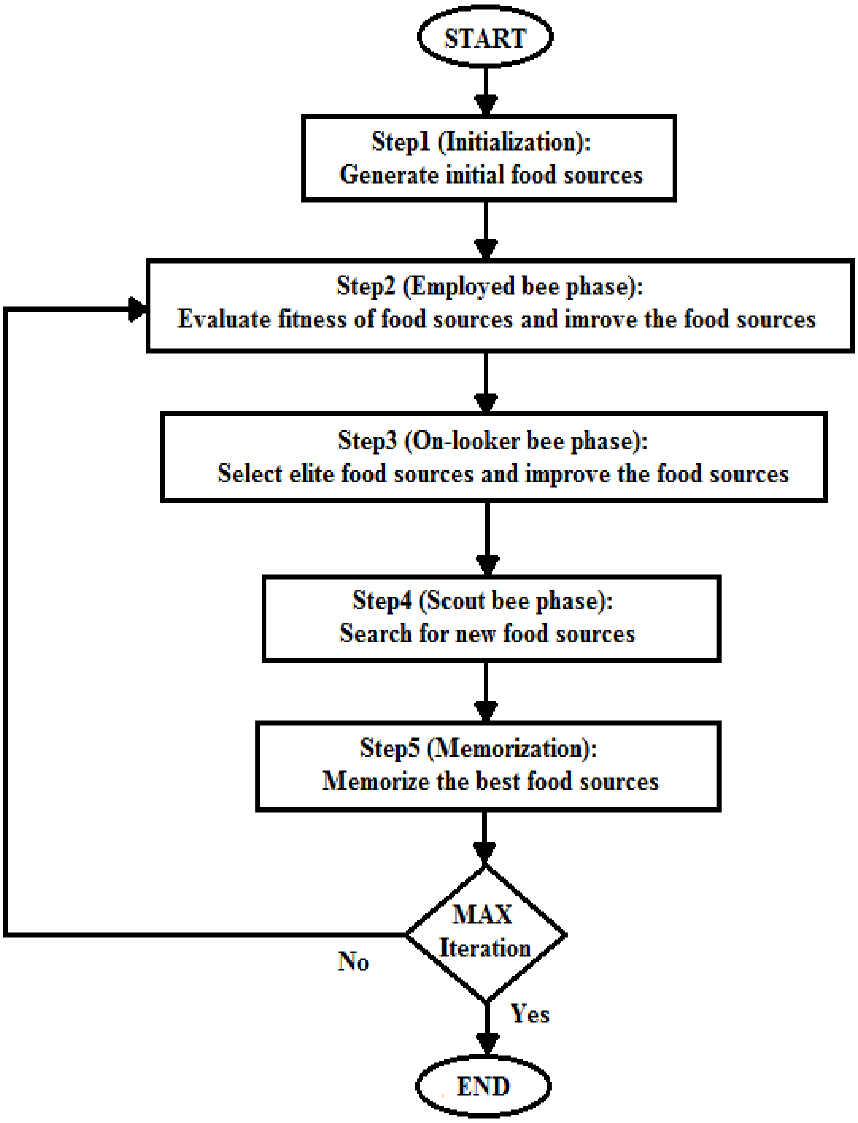

Fig.4 Flowchart of Bee Algorithm

VI. SIMULATION RESULTS

A. Results of Three Phase 7-level Cascaded Inverter

The simulation results on a three phase 7-level cascaded inverter fed from variable dc sources with 10% variations is given. In this study V1, V2 and V3 are assumed as follows:

$$V1 = 1 \pm 0.1,\ V2 = 0.9 \pm 0.09,\ V3 = 0.8 \pm 0.08$$

Assume that the fundamental component is $V_f = 2.419$ for 7-level inverters. There are 3^3 states for voltage sources in 7-level inverters and the relevant proper switching are obtained using PSO algorithm and Bee algorithm with fitness function relationship. The results of PSO & Bee algorithm are shown in TABLE1.

Number of particles	160
Number of variables	3
Max. number of Iterations	1000
Inertia weight factor (wmax)	0.9
Inertia weight factor (wmin)	0.6
Accelerating constant (c1)	2
Accelerating constant (c2)	2

Fig.5 Parameters of PSO & Bee algorithm for three phase 7-level Inverters

TABLE 1. PSO & Bee algorithm results for three phase 7-level Inverters

V1	V2	V3	Ɵ1	Ɵ2	Ɵ3
0.9	0.81	0.72	12.44061	34.69117	60.46533
0.9	0.81	0.8	13.44848	36.15185	61.14653
0.9	0.81	0.88	16.38265	40.61519	62.91117
0.9	0.9	0.72	13.48286	38.58278	63.5174
0.9	0.9	0.8	15.32014	40.79164	64.02365
0.9	0.9	0.88	17.34292	43.00056	64.23616
0.9	0.99	0.72	15.00197	41.8662	66.07264
0.9	0.99	0.8	17.07473	43.92358	65.92025
0.9	0.99	0.88	19.43166	46.05676	65.56234
1	0.81	0.72	15.50017	40.90136	63.26155
1	0.81	0.8	17.35158	43.3748	63.53373
1	0.81	0.88	19.39853	45.88965	63.49128
1	0.9	0.72	17.1962	44.41115	65.23565
1	0.9	0.8	19.3825	46.85174	64.7721
1	0.9	0.88	21.7413	49.27882	64.14288
1	0.99	0.72	19.29307	47.64648	66.3356
1	0.99	0.8	21.83137	50.0564	65.17296
1	0.99	0.88	24.40364	52.17212	64.27372
1.1	0.81	0.72	19.33952	47.87566	63.73927
1.1	0.81	0.8	21.91991	51.43306	62.46354
1.1	0.81	0.88	23.98272	54.39027	61.26016
1.1	0.9	0.72	22.32082	52.77598	62.75057
1.1	0.9	0.8	25.34207	56.88832	60.05056
1.1	0.9	0.88	7.79532	32.09038	90
1.1	0.99	0.72	24.56943	55.83171	61.51518
1.1	0.99	0.8	26.54189	58.91613	58.91615
1.1	0.99	0.88	11.0263	39.98619	85.98807

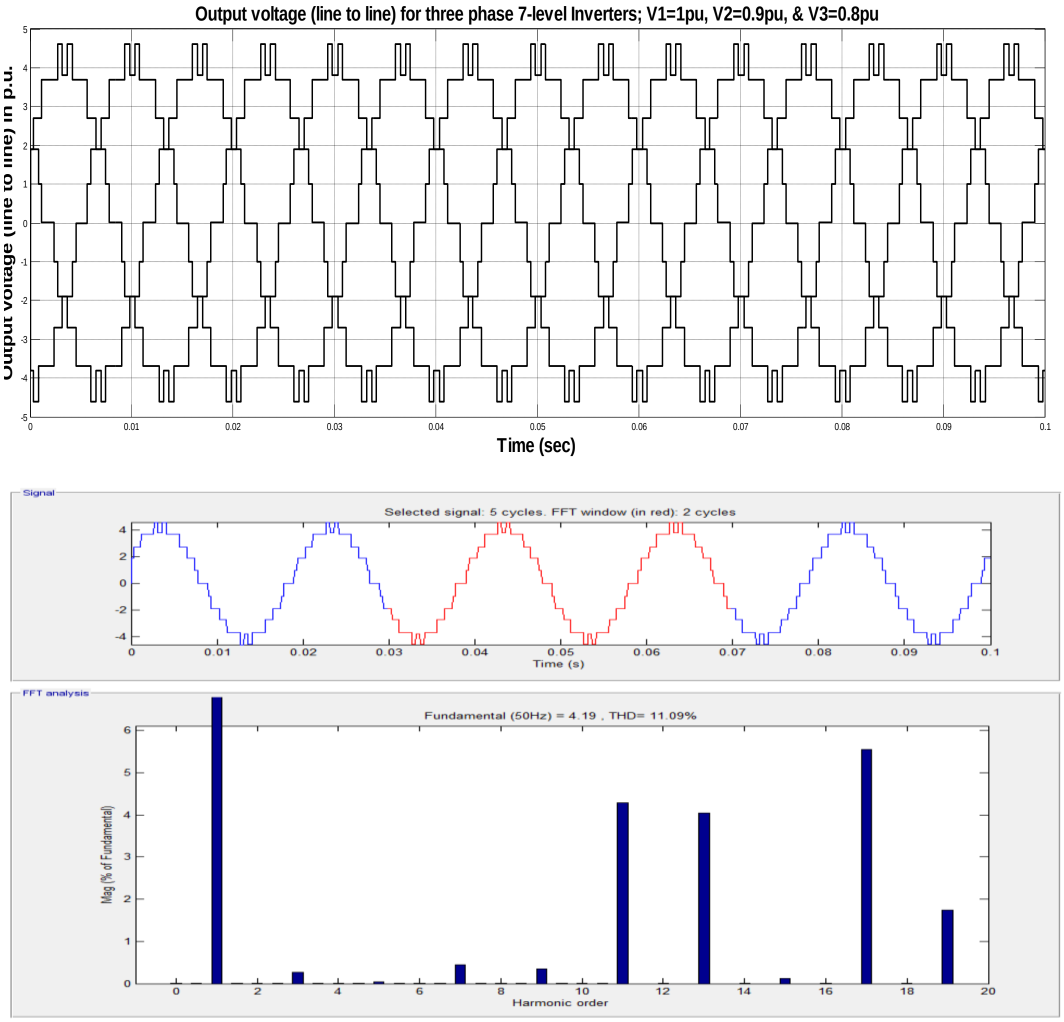

Fig.6 Output voltage & FFT result for three phase 7-level Inverters

B. Results of Three Phase 9-level Cascaded Inverter

The simulation results on a three phase 9-level cascaded inverter fed from variable dc sources with 10% variations is given. In this study V1, V2, V3 and V4 are assumed as follows:

$$V1 = 1 \pm 0.1,\ V2 = 0.9 \pm 0.09,\ V3 = 0.8 \pm 0.08,\ V4 = 0.7 \pm 0.07$$

Assume that the fundamental component is Vf = 3.05 for 9-level inverters. There are 3^4 states for voltage sources in 9-level inverters and the relevant proper switching are obtained using PSO algorithm with fitness function relationship. The parameters of PSO & Bee algorithm are shown in figure 7.

Number of particles	300
Number of variables	4
Max. number of Iterations	1000
Inertia weight factor (wmax)	0.9
Inertia weight factor (wmin)	0.6
Accelerating constant (c1)	2
Accelerating constant (c2)	2

Fig.7Parameters of PSO & Bee algorithm for three phase 9-level Inverters

This paper studies all sets (i.e. 81 states) of dc input voltage with 10% variation for three phase 9-level inverter, results of PSO & Bee algorithms are shown in the TABLE2.

TABLE 2. PSO & Bee algorithm results for three phase 9-level Inverters

V1	V2	V3	V4	Ɵ1	Ɵ2	Ɵ3	Ɵ4
0.9	0.81	0.72	0.63	10.26151	26.13045	44.86704	63.92794
0.9	0.81	0.72	0.7	11.25753	27.70965	46.59218	64.12955
0.9	0.81	0.8	0.63	10.62461	28.11223	46.87945	66.20735
:	:	:	:	:	:	:	:
0.9	0.81	0.88	0.63	8.596394	32.11692	46.21998	73.57974
0.9	0.81	0.88	0.7	4.529804	19.46785	38.60365	87.80127
0.9	0.81	0.88	0.77	7.717927	15.44766	35.94274	90
0.9	0.9	0.72	0.63	9.937297	34.3823	48.22328	72.30295
0.9	0.9	0.72	0.77	6.285639	34.8001	44.69944	79.42294
0.9	0.9	0.8	0.63	10.32999	32.96039	49.2304	71.36097
:	:	:	:	:	:	:	:
0.9	0.9	0.8	0.77	4.23757	20.09262	39.07978	88.5295
0.9	0.9	0.88	0.63	5.372663	29.90015	46.04826	78.4128
0.9	0.99	0.72	0.63	3.621097	21.10961	40.18326	88.46013
0.9	0.99	0.72	0.7	4.231107	20.32924	39.37841	89.17203
0.9	0.99	0.72	0.77	5.13627	31.38559	47.71889	82.5682
0.9	0.99	0.8	0.77	3.928019	29.77376	46.88438	82.5705
0.9	0.99	0.88	0.63	12.01791	34.23742	53.06246	70.99743
0.9	0.99	0.88	0.7	4.582227	30.27205	46.97959	79.89406
0.9	0.99	0.88	0.77	0	27.28362	45.31734	83.36844
1	0.81	0.72	0.63	6.904187	19.39177	37.53129	90
:	:	:	:	:	:	:	:
1	0.81	0.8	0.63	7.726805	32.86637	44.92668	76.54295
1	0.81	0.8	0.7	6.109892	20.04142	38.37742	88.91671
1	0.81	0.8	0.77	5.349896	21.92427	39.80603	87.95457
1	0.81	0.88	0.63	5.800889	29.4785	43.99161	80.5525
:	:	:	:	:	:	:	:
1	0.9	0.72	0.63	5.212534	22.80738	40.92303	87.8632
1	0.9	0.72	0.7	7.884137	35.13647	44.76486	76.59815
1	0.9	0.72	0.77	5.294822	22.2085	40.36128	88.55105
1	0.9	0.8	0.63	5.692961	29.76969	45.28065	81.17322
:	:	:	:	:	:	:	:
1	0.9	0.88	0.77	4.847517	29.7393	44.74492	82.27161
1	0.99	0.72	0.63	14.48016	37.26551	55.40236	68.09208
1	0.99	0.72	0.7	16.27753	38.93533	56.93091	66.67597
1	0.99	0.72	0.77	5.519063	30.24394	46.74731	83.65407
1	0.99	0.8	0.63	10.06541	30.13812	55.58331	87.69017
:	:	:	:	:	:	:	:

V1	V2	V3	V4	Ɵ1	Ɵ2	Ɵ3	Ɵ4
1.1	0.81	0.72	0.63	6.390111	26.21525	42.3231	86.0527
1.1	0.81	0.72	0.7	17.93994	39.74816	58.60023	63.55114
1.1	0.81	0.72	0.77	7.260491	20.59477	38.1535	90
1.1	0.81	0.8	0.7	6.376102	29.62093	43.46669	83.37735
:	:	:	:	:	:	:	:
1.1	0.9	0.88	0.7	21.33542	43.81351	60.443	63.15114
1.1	0.9	0.88	0.77	23.05509	45.94301	59.03272	66.32278
1.1	0.99	0.72	0.63	10.25737	30.0667	55.42392	88.4017
:	:	:	:	:	:	:	:
1.1	0.99	0.8	0.7	10.89528	28.66913	56.24108	90
:	:	:	:	:	:	:	:
1.1	0.99	0.88	0.77	24.72399	48.13283	58.9085	68.22316

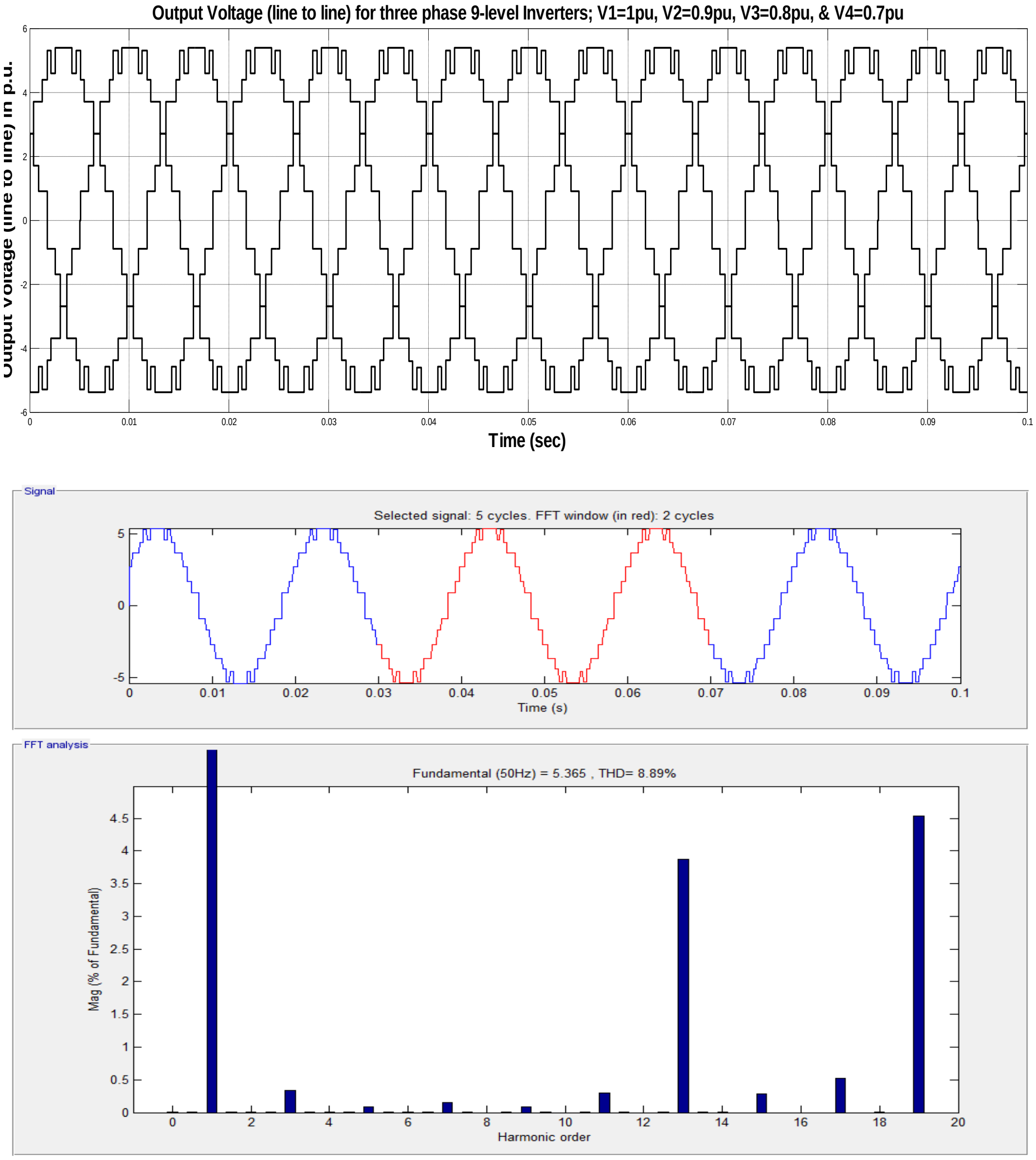

Fig.8 Output voltage & FFT result for three phase 9-level inverter

VII. CONCLUSION

This paper has been presented cascaded multilevel inverters in which the low order harmonic eliminated with non-equal dc voltage sources using soft computing techniques. The PSO and Bee algorithm are used to obtain the optimal switching angles for minimizing the low order harmonics and also getting the desired fundamental voltage for the three phase 7-level & 9-level cascaded inverters with the entire range of 10% increase and decrease in dc source voltage are covered. Simulation results provided to validate the accuracy of control method to minimize undesired low order harmonics by showing the output voltage waveforms and their corresponding FFT results in MATLAB Simulink.

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