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Selective Harmonic Minimization in Asymmetric Cascaded Multilevel Inverters using Soft Computing Methods

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Abstract: Multilevel Inverters (MI) achieve the desired output voltage by suitable combination of low dc variable voltages at the input side. The fundamental output voltage can be controlled and the undesirable lower order harmonics of stepped voltage waveform can be eliminated by applying Selective harmonic Elimination (SHE) Method. In this method, the commutation is provided for semiconductor switches on fundamental output voltage at predetermined angles. This paper proposes a Fuzzy Logic Controller to regulate the output voltage waveform of multilevel inverter with reduced harmonics. At first the Particle Swarm Optimization (PSO) algorithm is used to evaluate switching angles for different combination of input voltages applied to MLI and then a fuzzy controller is designed using PSO results to achieve the desired Fundamental output voltage and eliminate the low order harmonic for entire range of dc input voltage sources variation. The proposed FLC controlled method is carried out for a wider range of input dc voltages by considering ±10% variations in nominal voltage values to design 7 & 9-level inverter to validate the results obtained.

Keywords: H-bridge Multilevel Inverter, PSO, Fuzzy Controller, SHE method, THD.

I. INTRODUCTION

Multilevel Inverters had been introduced and are being developed to fulfill 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]. 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 and low cost solution. By Applying PSO algorithm, the values of switching angles are obtained for a predefined variation in DC voltage sources. Then fuzzy controller use the results of PSO algorithm, here fuzzy controller is use to cover entire range of 10% variations in DC voltage sources.

The PSO algorithm has been used to calculate 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

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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]. The paper is organized as chapter II & III include about H-bridge cascade multilevel inverter and selective harmonic method, chapter IV includes their problem formulation. Proposed methodology discuss in chapter V, and chapter VI & VII show the MATLAB simulation, FFT results and conclude the paper.

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 dc sources (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, +Vdc, 0 and -Vdc. 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.

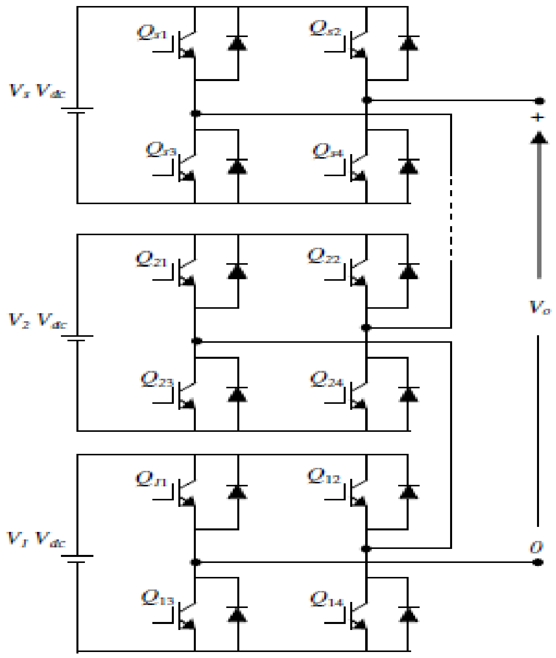

Figure 1 Single Phase Structure for Cascaded H-bridge Multilevel Inverter

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 waveform can 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 *Vs.Vdc* 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.

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

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$$(\mathrm{V1}.\cos(5\theta_1) + \mathrm{V2}.\cos(5\theta_2) + \cdots + \mathrm{Vs}.\cos(5\theta_s)) = 0$$

Where Vf is the amplitude of the fundamental component.

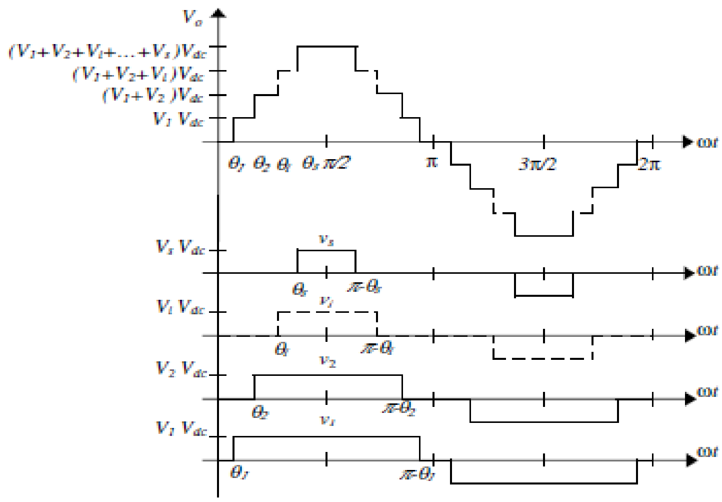

Figure 2 Generalized Output Voltage Waveform of a Cascaded Multilevel Inverter

IV. Problem Formulation

A. For three phase 9-level Cascaded Multilevel Inverters

Objective function:

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

Inequality constraint:

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

B. For three phase 7-level cascaded Multilevel Inverters

Objective function:

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

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 bird flocking or fish schooling [8].

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

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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 neighbors, the best value is a local best and is called lbest.

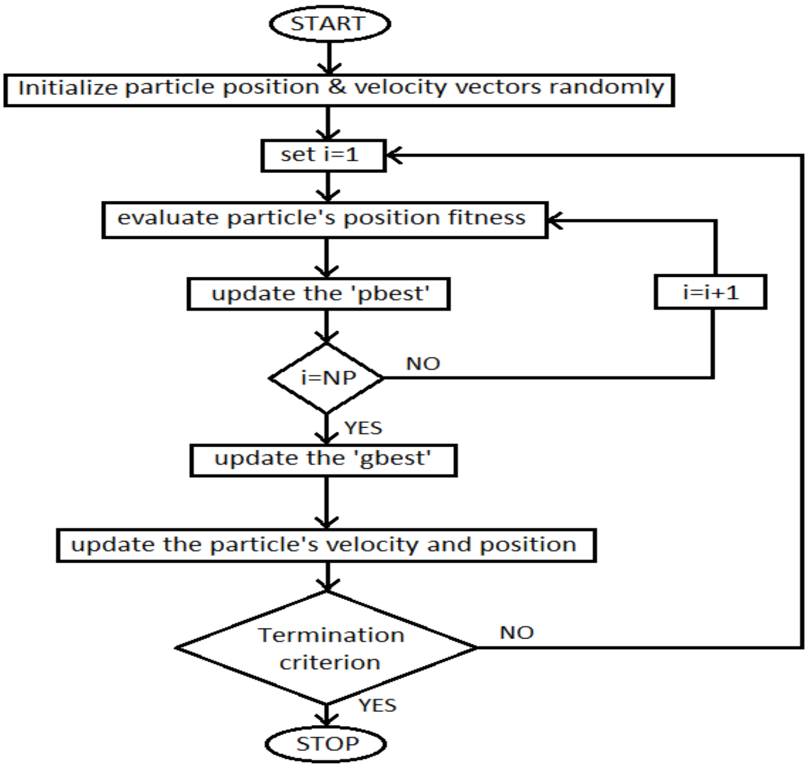

Figure 3 Flowchart of Particle Swarm Optimization (PSO)

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 c1 = c2 = 2.

B. **Fuzzy Logic Controller:**

Fuzzy logic is an approach to computing based on "degrees of truth" rather than the usual "true or false" (1 or 0) Boolean logic on which the modern computer is based. The process fuzzy reasoning is incorporated into what's called a Fuzzy Inferencing System. It consists of three stages process the system inputs at the appropriate outputs of the system. These steps are 1) Fuzzification, 2) Rules Assessment, and 3)Defuzzification.

1) Fuzzification: Fuzzification is the first step in the fuzzy inference process. This involves a domain transformation where the crisp datum are transformed into fuzzy datum. Crisp inputs are exact inputs measured by sensors and passed into the control system for the process.
2) Evaluation of the rule: the evaluation of the rule consists of a series IF-Operator-THEN rules. A decision structure to determine the rules require familiarity with the system and its desire process. This knowledge often requires the help of interview operators and experts.
3) Defuzzification: Defuzzification involves the process of transpose the fuzzy outputs to the crisp outputs. Here, the membership function makes it possible to define a set fuzzy by mapping the net values of his domain to related sets degree of membership, which is the degree of a crisp data is compatible with a membership function, value from 0 to 1, also known as truth value or fuzzy input.

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VI. SIMULATION RESULTS

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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 with fitness function relationship. The results of PSO are shown in TABLE1.

Number of particles	60
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

Figure 4 Parameters of PSO for three phase 7-level Inverters

Table 1 Particle Swarm Optimization (PSO) results for three phase 7-level Inverter

V1	V2	V3	ϴ1	ϴ2	ϴ3
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	89.9835
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

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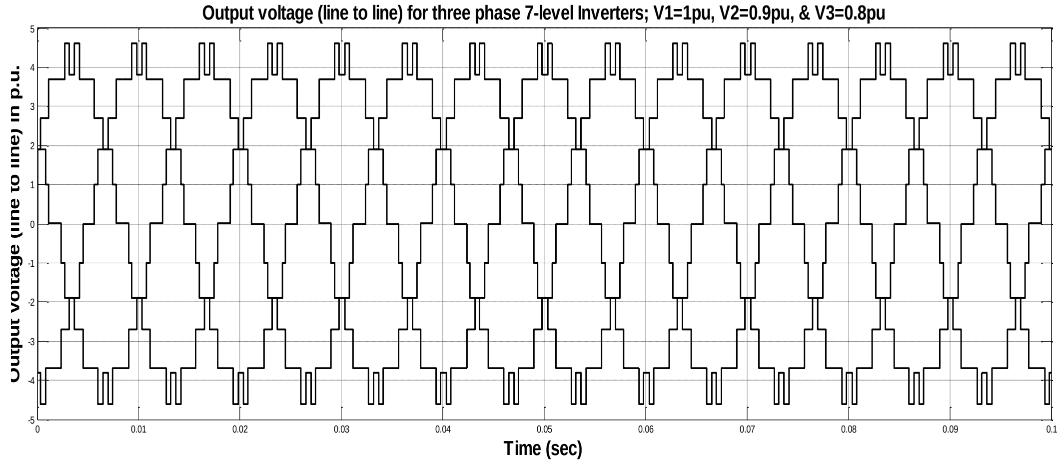

Figure 5 Output voltage for three phase 7-level Inverters

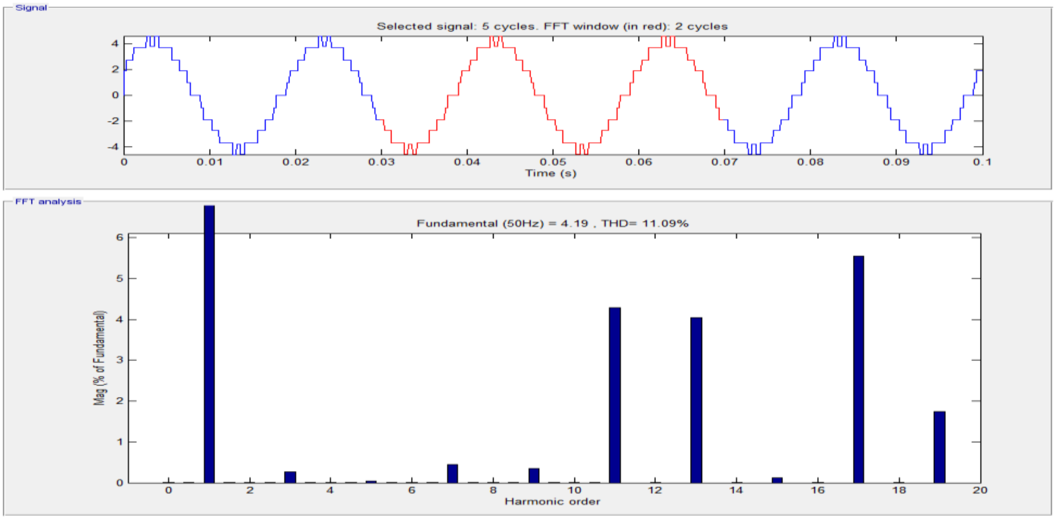

Figure 6 FFT result for three phase 7-level Inverters

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 $V_f = 3.05$ 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 are shown in figure 7.

Number of particles	60
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

Figure 7 Parameters of PSO for three phase 7-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 are shown in the TABLE2.

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Table 2 Particle Swarm Optimization (PSO) results for three phase 9-level Inverter

V1	V2	V3	V4	ϴ1	ϴ2	ϴ3	ϴ4
0.9	0.81	0.72	0.63	5.673402	19.57401	38.1309	89
:	:	:	:	:	:	:	:
0.9	0.81	0.8	0.77	0	24.14985	42.04356	85.1884
0.9	0.81	0.88	0.63	6.257107	17.21531	37.04529	89
:	:	:	:	:	:	:	:
0.9	0.9	0.72	0.63	4.952971	20.01945	38.78351	89
:	:	:	:	:	:	:	:
0.9	0.9	0.88	0.63	0	24.49321	42.74068	83.84396
:	:	:	:	:	:	:	:
0.9	0.9	0.88	0.77	5.1014	18.30577	37.88617	89
0.9	0.99	0.72	0.63	4.157653	20.41192	39.46136	89
:	:	:	:	:	:	:	:
0.9	0.99	0.88	0.63	0	26.29366	44.80812	82.46643
0.9	0.99	0.88	0.7	4.362892	18.68255	38.29566	89
1	0.81	0.72	0.63	6.246895	20.81083	38.74506	89
:	:	:	:	:	:	:	:
1	0.9	0.72	0.63	5.694061	21.17241	39.41668	89
:	:	:	:	:	:	:	:
1	0.9	0.8	0.63	4.986303	27.96847	44.51563	82.8998
1	0.9	0.88	0.63	11.52216	30.11679	56.7681	89
1	0.9	0.88	0.7	5.660954	19.34256	38.29478	89
:	:	:	:	:	:	:	:
1	0.99	0.72	0.77	4.980367	21.79942	40.42372	89
1	0.99	0.8	0.63	10.21159	28.80113	55.75925	89
1	0.99	0.8	0.7	4.955916	20.74738	39.52371	89
1	0.99	0.88	0.63	10.72765	29.08715	56.2467	89
:	:	:	:	:	:	:	:
1.1	0.81	0.72	0.63	10.19598	34.72908	45.53607	71.72843
1.1	0.81	0.72	0.7	6.781062	22.1735	39.46269	89
1.1	0.81	0.8	0.63	6.523793	29.63211	43.57778	82.45956
1.1	0.81	0.8	0.7	6.668776	21.13934	38.8356	89
:	:	:	:	:	:	:	:
1.1	0.81	0.88	0.63	6.231911	29.18335	43.41045	81.77437
1.1	0.81	0.88	0.7	6.647188	20.08146	38.2868	89
:	:	:	:	:	:	:	:
1.1	0.9	0.8	0.63	11.57442	30.95914	56.78747	89
:	:	:	:	:	:	:	:
1.1	0.99	0.72	0.63	10.29365	29.39145	55.48101	89
:	:	:	:	:	:	:	:
1.1	0.99	0.88	0.63	11.26914	30.07057	56.52324	89
1.1	0.99	0.88	0.77	11.27838	30.37692	56.53259	89

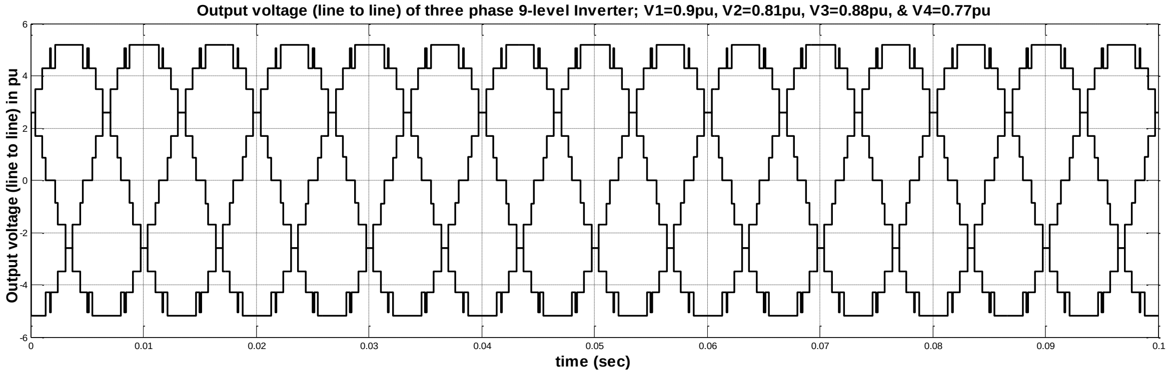

Figure 8 Output voltage for three phase 9-level Inverters

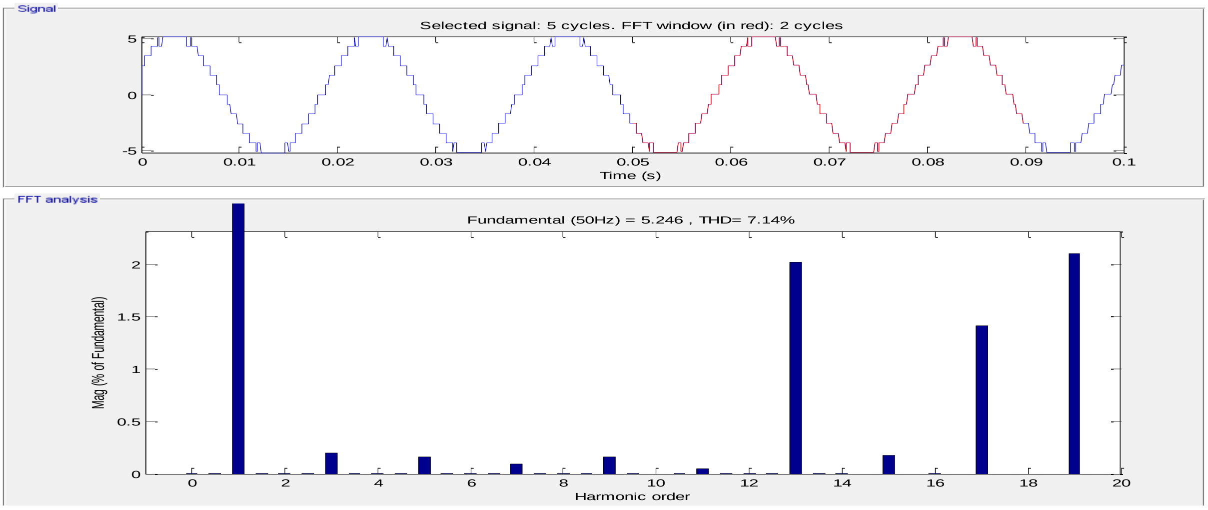

Figure 9 FFT result for three phase 9-level Inverters

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 algorithm is used to obtain the optimal switching angles for minimizing the low order harmonics and get the desired fundamental voltage for 7-level & 9-level cascaded inverters. This optimal value of switching angles, which obtained by PSO algorithm, used for designing the fuzzy logic controller, hence entire range of 10% increase and decrease in dc source voltage was covered. Simulation results provided to minimize undesired low order harmonics by showing the output voltage waveforms and their corresponding FFT results in MATLAB Simulink.

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