FUNDAMENTAL FREQUENCY MODULATED CASCADED H BRIDGE INVERTER USING IMPROVED FIREFLY ALGORITHM

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Abstract: Fundamental Frequency modulation strategy is particularly well suited for high-power applications where the power losses have to be kept below strict limits. A key concern in the fundamental switching scheme is to determine the switching angles in order to produce the fundamental voltage and not to generate specific lower order harmonics. This paper presents an estimation of optimum switching angles for seven and nine level cascaded H Bridge Multilevel Inverter (CHB MLI) to eliminate pre specified order of Harmonics using improved Firefly Algorithm. Estimation of the optimum switching angles is a difficult task as it involves solving a set of trigonometric transcendental equations. However with heuristic search algorithms it is possible to estimate the solutions within the limits of allowable tolerances even if the number of equations is large. Though number of optimization algorithms available for numerically solving these equations, Firefly Algorithm (FA) takes minimum execution time and outperforms all other 11 Meta heuristic Algorithms. The algorithm and model are developed using MATLAB and the simulation results reveal that the proposed technique offers the maximum available fundamental voltage for the dc voltage levels with the selected lower order harmonics eliminated. Furthermore the simulation results are verified experimentally using FPGA Spartan 6A DSP setup.

Key Words: *Fundamental Frequency modulation, Multilevel Inverter, Firefly Algorithm, FPGA*

I.INTRODUCTION

Multi level inverters have been proven popular for medium, high voltage and high power applications due to their various advantages like lower common mode voltage, lower voltage stress on power switches, lower dv/dt ratio to supply lower harmonic contents in output voltage and current[1,2]. Since their output voltage is a modulated staircase, they outperform two-level PWM inverters in terms of total harmonic distortion (THD), without the use of bulky expensive and dissipative passive filters. Therefore, recently, they have been proposed in the field of renewable energies, including Solar PV applications. The diode clamped [3] inverters, the flying capacitor model [4, 5] and the cascaded multi level inverters are the most common multi level inverter topologies.

If the number of available distinct and isolated DC sources are more than one, then these DC sources can be integrated into a common inverter using the cascaded multi level inverter configuration [6-10]. The output voltage is a staircase waveform synthesized by alternating the contributions of multiple H-bridges at each half-cycle.

In [8] & [11], the authors have discussed about the many techniques used for switching the multi level inverter with fundamental switching frequency scheme. The Selective Harmonic Elimination pulse with modulation(SHE PWM)is one among the various low frequency switching strategies which offers tight control of the harmonic spectrum of a given voltage and/or current waveform generated by a power electronic converter. High distortion is produced in the load voltage and current due to side bands around the carrier frequency appear as low order harmonics, if we use conventional PWM methods like SVPWM & sub Harmonic PWM below 1 kHz range. The advantage of this PWM over sinusoidal PWM is that better quality of output is obtained at lower switching frequency & the input dc sources are not necessarily be equal . In SHE there is an analytical difficulty of solving a set of non linear trigonometric transcendental equations. The predominant method of solving the transcendental equations is by means of iterative techniques including the Newton Raphson technique [12-15]. The function to be solved should necessarily be differentiable and that proper initial guess is required. The Newton Raphson method gives the solution that is next nearest as dictated by the initial guess. Another analytical method is the theory of resultants and it is capable of finding all feasible solutions [16]. Considering the mathematical complexity, the theory of resultants is a difficult procedure especially when handling more number of levels and it is much more complicated when the operating DC voltage sources vary from time to time in real time. In [17] higher order harmonics are eliminated by simply producing the opposite of the harmonics to cancel them .Another method for real time calculation of switching angles has been proposed in [18], which is based on the quadratic curve fitting of trajectories of the precise switching angles.

In [19] & [20], Genetic Algorithm is applied to SHE problem. But when the number of levels increases, there is a probability of ending up with local optima as the search space increases. But the exact limitations of these algorithms cannot be determined.

The estimation of switching angles by solving the SHE equations have been demonstrated by using other heuristic search algorithms typically like the Particle Swarm Optimization [21,22], Bacterial Foraging Algorithm [23], Ant Colony Algorithm [24] and the Bee Algorithm [25].

In this manuscript, nature inspired Meta heuristic algorithm known as improved Firefly algorithm [26] is used to obtain optimum switching angles for seven and nine level CHB MLI. This method gives better results than original FA as it depends on its parameters such as absorption and attraction coefficients and random movement factor which leads to probability of ending up with local optima.

Both MATLAB simulation and experimental verifications have been carried out and the results are summarised. The results reveal that the proposed methodology offers the maximum available fundamental voltage for the available DC voltage levels of the isolated DC sources with the selected lower order harmonic eliminated for whatever be the source voltages and whatever be the magnitude of the fundamental voltage.

After the introduction in chapter I the rest of the paper is arranged as follows. Chapter II describes the working of CHB MLI. Chapter III gives a brief introduction to SHE PWM as applied to multi level inverters using Step modulation.. Chapter IV gives the details of how the FA is employed to handle the problem at hand. Chapter V discusses the results of simulation and experimental verification followed by the conclusion.

II.Cascaded Multilevel Inverter Topology

This topology is known as symmetrical *m*-cell CHB converter and it contributes great properties like high modularity and less number of switches. One aspect which sets the cascaded H-bridge apart from other multilevel inverters is its ability to utilize different dc voltages on the individual H-bridge cells [9], [10]. Several three-level power cells formed by full H-bridges can be combined to build a converter with a higher number of levels. In general, if *m* power cells are connected in series to achieve 2*m*+1 number of levels Fig.1 shows a single-phase structure of a cascaded inverter with Separate DC Sources (SDCS). As the output side of the CHB inverter is connected in series, sources at the input side should be isolated from each other. Due to this property, H bridges are supplied from renewable energy sources like fuel cells ,Photo Voltaic arrays etc [2].Hence Each inverter can generate three different voltage outputs $+V_{dc}$, 0, $-V_{dc}$ at the ac output side by turning on different combinations of the four switches S_1 ,S_2 , S_3 and S_4 of each bridge. To obtain $+V_{dc}$, switches S_1 and S_4 are turned on, whereas $-V_{dc}$ can be obtained by turning on switches S_2 and S_3. By turning on S_1 and S_2 or S_3 and S_4, the output voltage is 0.

Phase voltage waveform for 9 level cascaded multilevel inverter with four isolated dc sources (S = 5) is shown in Fig.2. Each H-bridge unit generates a quasi-square waveform by phase-shifting the switching timings of its positive and negative phase legs.

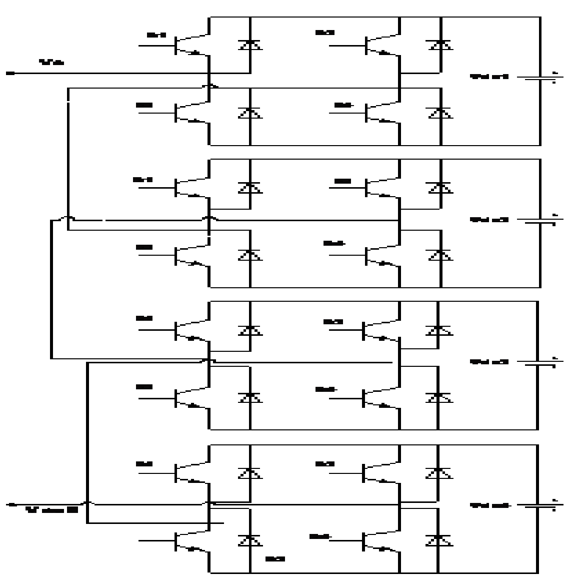


Figure. 1. Structure of nine level cascaded H bridge

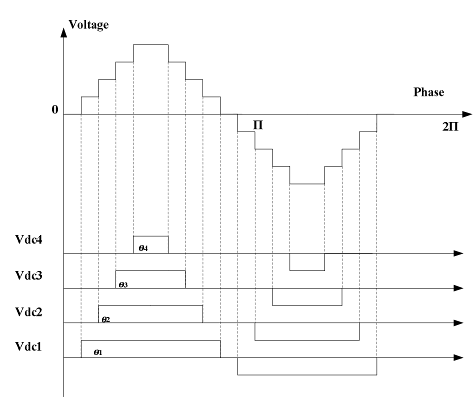


Figure. 2. Output voltage waveform of a 9-level MLI

multilevel inverter

III.Fundamental Frequency Modulation Strategy

The problem of instability takes place in converters due to the harmonics which are integral multiples of the fundamental frequency. There are diverse modulation techniques in fundamental switching frequency available for multilevel inverters such as sinusoidal PWM, space vector PWM, SHEPWM [2, 11]. The space vector PWM and sinusoidal PWM fail to succeed with non equal sources. The promising fundamental frequency modulation scheme for the multilevel CHB inverter is staircase modulation with selective harmonic elimination [12-14]. One of the greatest benefits of this staircase waveform is that he switches in the inverters only need to be switched on and off once during one fundamental cycle; thus, the switching loss of the devices is reduced to minimum. This technique is applied to a particular operating point aiming to obtain the optimum position of these switching transitions that offer elimination to a selected order of harmonics. For getting a certain fundamental output voltage, each level is appropriately positioned on each other with quarter wave symmetry. The distance each level maintains from the y axis is called the switching angle. These switching angles $\theta_1, \theta_2, \theta_3, \theta_4$, the amplitude of the fundamental of the output AC voltage and the DC source voltages are all related by a set of trigonometric transcendental equations. These equations when solved can give the switching angles $\theta_1, \theta_2, \theta_3, \theta_4$ for the different levels when the modulation index and the operating DC voltages are given.

A 9 level inverter waveform is shown in Fig.2. It has four switching angles θ1, θ2, θ3 and θ4. Taking into consideration the waveform characteristics of odd and half-wave symmetry, the Fourier series expansion of the generalized stepped voltage waveform is given as follows:

$$V(\omega t) = \sum_{n=1}^{\infty} \frac{4\mathrm{Vdc}}{\mathrm{n}\pi} ((\cos n\theta 1) + (\cos n\theta 2) + (\cos n\theta 3) + \quad + (\cos n\theta s))\sin n\omega t) \qquad (1)$$

The switching angles θ1-θs must satisfy the following condition:

$$0 \leq \theta_1 \leq \theta_2 \leq \theta_3 \leq \theta_4 \text{---} \leq \theta_s \leq \frac{\pi}{2} \qquad (2)$$

The number of harmonics to be eliminated from the output of the inverter is S-1. The harmonics of the order up to 3S-2 when S is odd and up to 3S-1 when S is even can be eliminated from the output waveform[22].Therefore using 9 level inverter with 4 dc sources, three harmonics 5^{th} ,7^{th}, and 11^{th} can be eliminated and the transcendental equations to be satisfied are as follows

$$\cos(\theta_1)+\cos(\theta_2)+\cos(\theta_3)+\cos(\theta_4) = M*S$$

$$\frac{4\mathrm{Vdc}}{5\pi}[\cos(5\theta_1)+\cos(5\theta_2)+\cos(5\theta_3)+\cos(5\theta_4)] = V_5$$

$$\frac{4\mathrm{Vdc}}{7\pi}[\cos(7\theta_1)+V_{dc2}\cos(7\theta_2)+\cos(7\theta_3)+\cos(7\theta_4)] = V_7$$

$$\frac{4Vdc}{11\pi}[\cos(11\theta_1)+\cos(11\theta_2)+\cos(11\theta_3)+\cos(11\theta_4)] = V_{11} \quad (3)$$

where V_1 is the fundamental voltage and V_5, V_7, and V_{11} are target harmonic voltages to be eliminated.

For three-phase power system applications the elimination of triplen harmonics is not essential as they get cancelled from line-line automatically. To obtain the optimum switching angles the modulation index M, is defined to be a representative of V_1.

$$M = \frac{V_1}{4SV_{dc/\pi}};\ 0 \leq M \leq 1 \quad (4)$$

Firefly Algorithm

Meta Heuristic Algorithms are often nature inspired and they are the mostly used algorithms for optimization. Firefly Algorithm is the best among all other 11 Metaheuristic Algorithms.It is developed by Yang in 2009 [26]. It is inspired by social behaviour of fireflies or lightning bugs , a insect in tropical or summer region.There are three rules to be followed in this algorithm

i) all fireflies are unisex hence they move irrespective of their sex and there is no cross over procedure as in GA ii) the attractiveness is proportional to brightness and increasing with decreasing cartesian or Eucledean distance.Less brighter one will move toward more brighter one.If none of the firefly in the colony is brighter,they move randomly iii) Brightness is determined by the value of the objective function.

In this paper self adaptive modified Firefly Algorithm is used to obtain optimum switching angles.This method is better than original FA as it depends on its parameters such as absorption and attraction coefficients and random movement factor.Hence there is a probablity of ending up with local optima.Using modified FA,the performance can be effectively improved by adding a new mutation operator with the original FA.

FA consists of no. of fireflies with different brightness & the firefly with the best fitness function among all the fireflies is selected

$$Gbest^k = \left[best_1^k,\quad best_2^k,\qquad ,\quad best_N^k\right]$$

$$\theta_m^k = \left[\theta_{m,1}^k,\quad \theta_{m,2}^k,\qquad ,\quad \theta_{m,N}^k\right]$$

Where $m = 1, \dots, N_{firefly},$ N=no.of decision variables

$$\theta_{mod,firefly}^k = \begin{cases} \theta_{m,firefly}^k + \beta^k\left(\theta_{n,firefly}^k \quad \theta_{m,firefly}^k\right) + \alpha^k\left|\theta^{max} \quad \theta^{min}\right|(rand_{1\times N}(.) \quad 0.5); \\ \qquad if\ FF\left(\theta_{n,firefly}^k\right) < FF\left(\theta_{m,firefly}^k\right) \\ \theta_{m,firefly}^k; \quad Otherwise \end{cases}$$

(5)

$m = 1, \dots, N_{firefly}$ $n = 1, \dots, N_{firefly}$; FF is the fitness function

$$\theta^{max} = [\theta_1^{max},\quad \theta_2^{max},\quad \dots,\quad \theta_N^{max}];\ \theta^{min} = [\theta_1^{min},\quad \theta_2^{min},\quad \dots,\quad \theta_N^{min}]$$

Where β is the degree of attractiveness, which is a function of distance between two fireflies and it is expressed as

$$\beta^k = \beta_{max} e^{-\gamma (r_{mn,}^k)^p}$$
(6)

In this paper β^k is modified so as to result faster convergence of the algorithm and escaping from local optima and is given as follows

$$\beta^k = (\beta_{max} \quad \beta_{min}) e^{-\gamma (r_{mn}^k)^p} + \beta_{min} \tag{7}$$

Where γ is called as absorption coefficient which controls the reduction of light intensity and its value lies between 0 and 10 and p=2. [27].

$$r_{mn}^k = \left\| \theta_{n,firefly}^k \quad \theta_{m,firefly}^k \right\|$$

$$= \sqrt{\sum_{i=1}^{N} \left(\theta_{n,firefly}^k \quad \theta_{m,firefly}^k \right)^2}$$
(8)

Mutation Strategy: In order to improve the performance of the original FA and escape from local optima, a new powerful mutation strategy is devised. In each iteration, for each of the existing solutions, four vectors q_1, q_2, q_3, and q_4 are selected randomly from the existing population to cover the algorithm searching domain uniformly. However, for the four aforementioned vectors with limitation $q_1 \neq q_2 \neq q_3 \neq q_4 \neq m$ a mutant individual ($\theta_{m,mut}^k$) is generated as follows:

$$\theta_{m,mut}^k = \theta_{q1,firefly}^k + \begin{pmatrix} rand1(.)(1 \quad rand2(.))(\theta_{q2,firefly}^k \quad \theta_{q3,firefly}^k) + \\ rand3(.)(1 \quad rand4(.))(Gbest^k \quad \theta_{q4,firefly}^k) \end{pmatrix}$$
(9)

Then, the mutant vector is mixed with $\theta_{m,firefly}^k$ which generates $\theta_{m,new}^k$ as follows

$$\theta_{m,mut}^k = [\theta_{m,1,mut}^k, \quad \theta_{m,2,mut}^k, \quad \dots, \quad \theta_{m,N,mut}^k]$$

$$\theta_{m,new}^k = [\theta_{m,1,new}^k, \quad \theta_{m,2,new}^k, \quad \dots, \quad \theta_{m,N,new}^k]$$

$$\theta_{m,i,new}^k = \begin{cases} \theta_{m,i,mut}^k, & if\ (rand5(.) \leq rand6(.)) \\ \theta_{m,i,firefly}^k, & ot\ erwise \end{cases}$$

$m = 1, \dots, N_{firefly}$

where $\theta_{m,i,new}^k$ is the switching angle of the i th switch of m^{th} firefly of the k^{th} iteration. The new solution will replace the original solution based on its fitness function as follows

$$\theta_{m,firefly}^{k+1} = \begin{cases} \theta_{m,new}^{k}, & if\ FF(\theta_{m,new}^{k}) \leq FF(\theta_{m,firefly}^{k}) \\ \theta_{m,firefly}^{k}, & ot\ erwise \end{cases}$$

(10)

Fitness Function (*FF*): An appropriate fitness function is adopted that will maximise the fundamental voltage and eliminate the lower order harmonics and it is defined as.

$$Min\,FF = 100\ \frac{(V1d-V1)^4}{V1d^4} + \left(\frac{50}{V1}\right)^2\ \{\left(\frac{V5}{5}\right)^2 + \left(\frac{V7}{7}\right)^2 + \left(\frac{V11}{11}\right)^2\}$$ → Nine level MLI (11)

$$Min\,FF = 100\ \frac{(V1d-V1)^4}{V1d^4} + \left(\frac{50}{V1}\right)^2\ \{\left(\frac{V5}{5}\right)^2 + \left(\frac{V7}{7}\right)^2\}$$ → Seven level MLI (12)

Steps for Implementation of Improved Firefly algorithm to Fundamental frequency modulation Technique

Step 1: Assign the constants of FFA viz. *βmin, βmax,γ, p*, no. of fireflies, maximum no. of iterations. In this work the above said constants are taken as *βmin*=0.2, *βmax*=1,*γ*=1, *p*=2, maximum no. of iterations=200. Switching angles of MLI be the position of fireflies. The fitness value corresponding to the position of each firefly be the brightness of firefly.

Step :2 Initialize the position of fireflies by randomly generating the switching angles between minimum and maximum limit satisfying eq. (2). It may be noted that more number of fireflies result in larger computing time whereas a smaller number of fireflies result in a local minima. Hence in this paper the number of fireflies is taken as 20.

Step 3: Evaluate the brightness (i.e fitness value) for each firefly using eq. (11 or 12).

Step 4: Update the position of fireflies using eq.(5 to 10) and the firefly corresponding to minimum fitness value is stored in Gbest.

Step 5: Repeat steps 2 to 4 until the stopping condition is met. In this work maximum iteration is considered as stopping criterion.

IV.Results And Discussion

To verify the validity of the solutions obtained with the improved FFA proposed in this paper, simulations based on MATLAB simulink for seven and nine-level cascade inverter are carried out. The algorithm is developed using MATLAB software on a Intel(R) core i3 2.4 GHz CPU with memory of 3GB RAM for seven level and nine level MLI.

The parameters for simulation are as follows: voltage of a level (Vdc)= 12 V, frequency of the output voltage, *f* =50 Hz, the resistance and inductance of the load are *R* = 100 Ω , L=100 mH respectively. The effectivenesss of the proposed solution is demonstrated for two cases.

Case 1: Seven Level Cascaded MLI

For finding the optimal switching angles for various modulation index (MI) values, the modified FA is run with selected parameters over 20 independent runs of 100 iterations in each trial and the best solution is summarized in Table 1. It is interesting to find that, FA yields best solution in every independent trial and the number of hits towards global solution is found to be 100%. Then the switching angles are fed to the Multilevel Inverter built using MATLAB simulink and the Harmonic spectrum is obtained. It is explicitly shown that self adaptive modified FA gives optimized swiching angles such that lower order Harmonics are almost eliminated & THD is much less even for phase voltage.

Figure 3 & 4 shows the harmonic spectrum and output voltage waveform respectively for the MI values of 0.8 and 0.6 and Vdc=12V. It is found that the lower order harmonics 5th & 7th are well mitigated and the desired fundamental voltage is achieved.

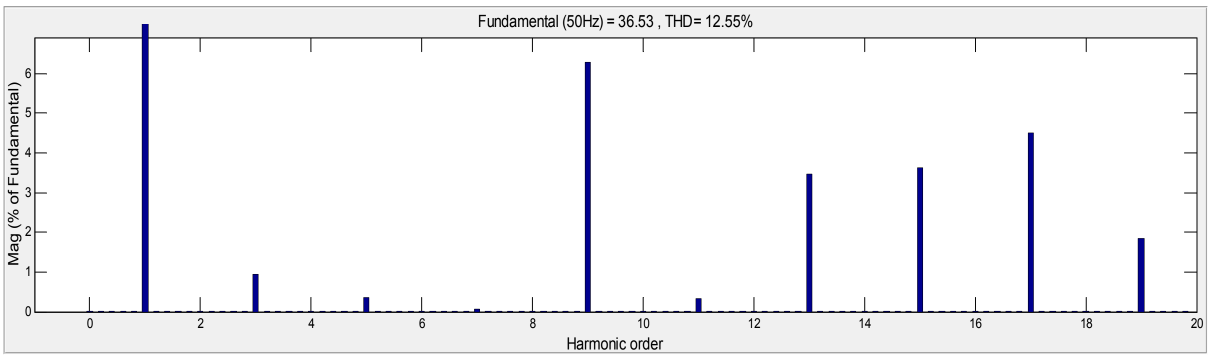


Figure 3(a)

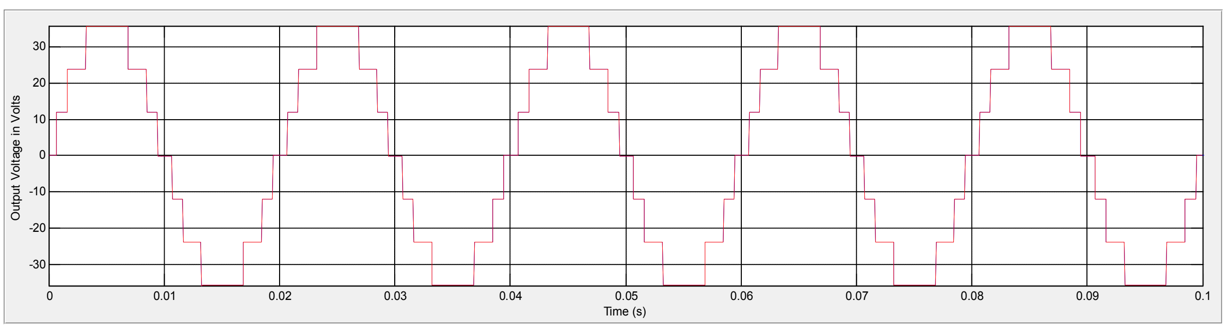


Figure. 3(b)

Figure.3(a) Harmonic Spectrum 3(b) Output Volage waveform of 7 Level MLI for MI of 0.8

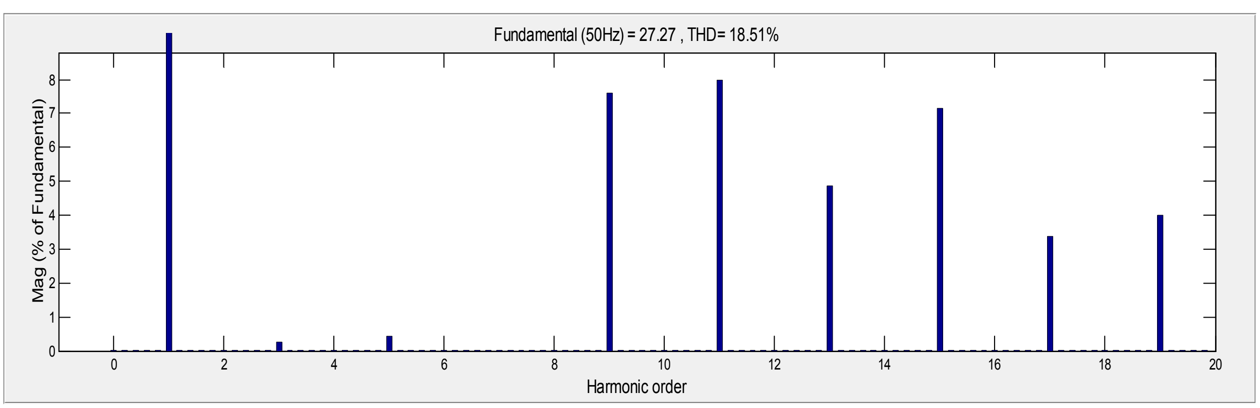


Figure.4(a)

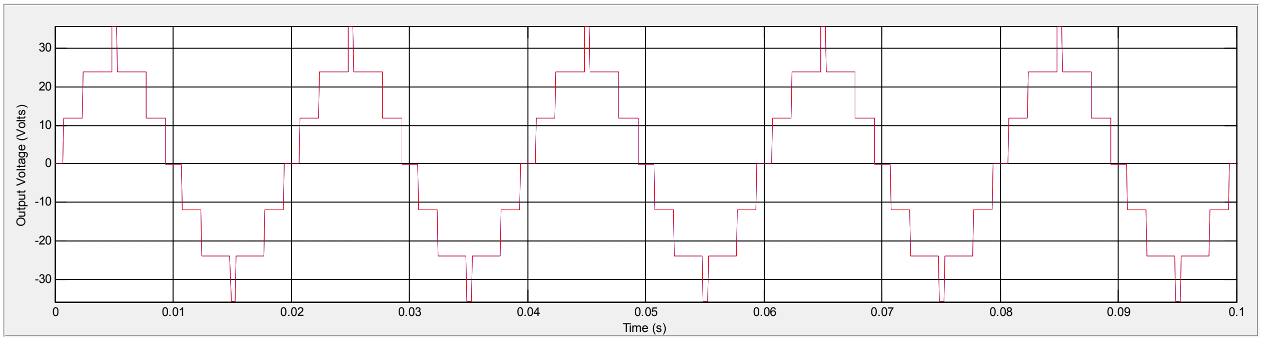


Figure.4(b)

Figure 4(a) Harmonic Spectrum 4(b) Output Volage waveform of 7 Level MLI for MI of 0.6

Table 1 shows the optimum switching angles obtained from proposed FFA for the MI of 0.6 and 0.8 and the respective THD values.

Table 1: Optimum Switching Angles and THD of 7 Level MLI

Modulation Index (MI)	Optimum Switching Angles Obtained from FA algorithm (degrees)			THD (%)
	θ_1	θ_2	θ_3	
0.8	11.5041	28.7257	57.1118	12.55
0.6	11.7920	41.6684	85.7215	18.51

It is found that the FA reaches global optima rapidly with more precision. Table 2 shows the Lower order harmonic content and THD for varying Modulation Index for 7 Level MLI. The THD is found to be high for lower modulation index of 0.4 and it decreases with increasing MI. Also the lower order harmonic content is found to be negligible.

Table 2: Lower order harmonic content and THD for varying Modulation Index for 7 Level MLI

Modulation Index (MI)	h5 (%)	h7 (%)	THD (%)	Fundamental voltage V1(Peak in Volts)	
				Theoretical	Simulation
0.4	0.66	0.06	49.37	18.33	18.22
0.5	0.52	0.0.09	23.12	22.91	22.84
0.6	0.42	0.01	18.51	27.49	27.27
0.7	0.10	0.19	22.54	32.08	31.84
0.8	0.03	0.31	**12.55**	**36.66**	**36.53**

From Table 2 it is evident that target lower order harmonics of order 5 and 7 are almost eliminated and also the desired fundamental voltage is achieved.

Case 2: Nine Level cascaded MLI

Table 3 shows the optimum switching angles obtained from FA and The THD for the MI of 0.6 and 0.8. It is found that the target lower order harmonics 5^{th}, 7^{th} and 11^{th} are well mitigated and also THD value is found to be less compared to seven level MLI.

Table3: Optimum Switching Angles and THD of 9 Level MLI

Modulation Index (MI)	Optimum Switching Angles obtained from FA algorithm (in degrees)				THD (%)
	θ_1	θ_2	θ_3	θ_4	
0.8	9.7313	20.4619	38.4858	60.5219	9.68
0.6	11.6137	28.5595	56.9874	89.9366	12.88

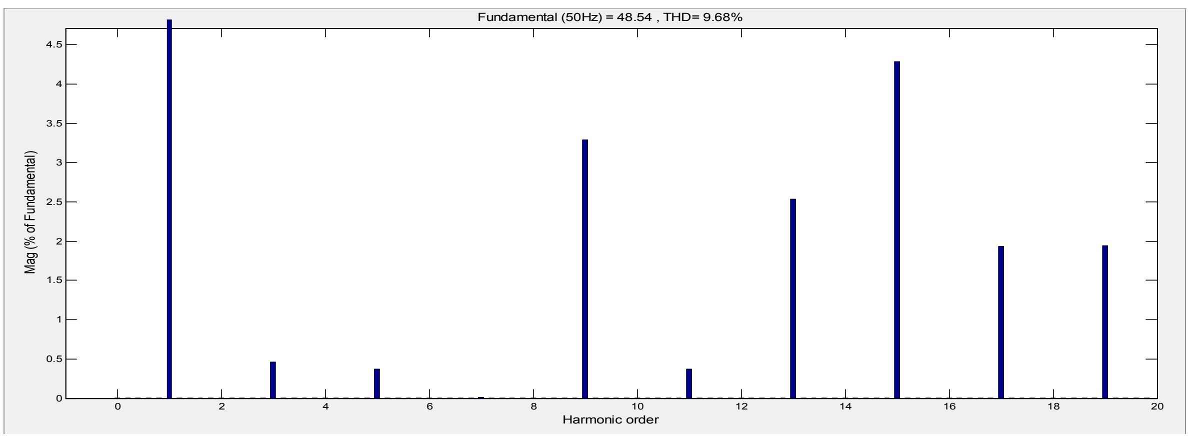


Figure5(a)

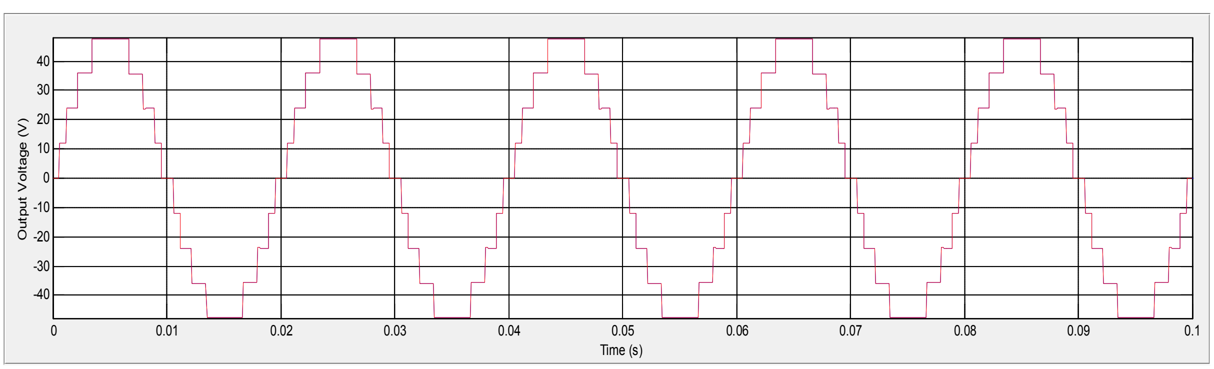


Figure.5(b)

Figure 5(a) Harmonic Spectrum 5(b) Output Volage waveform of 9 Level MLI for MI of 0.8

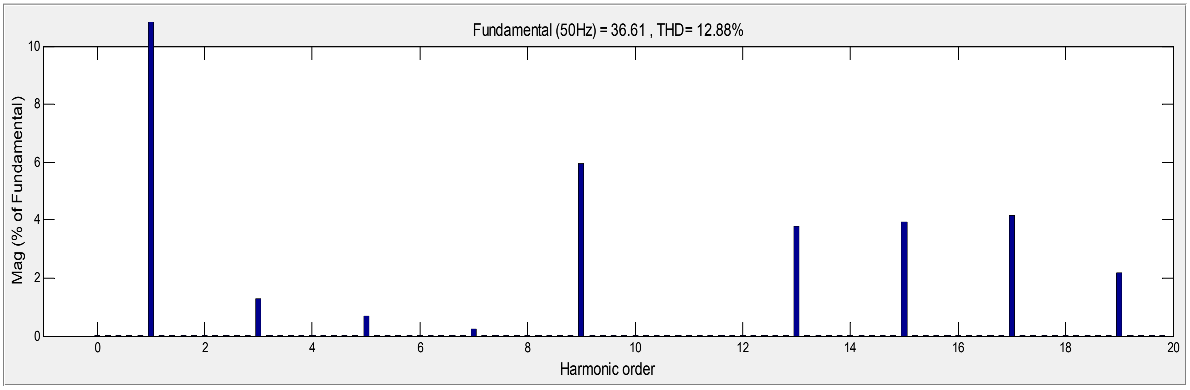


Figure 6(a)

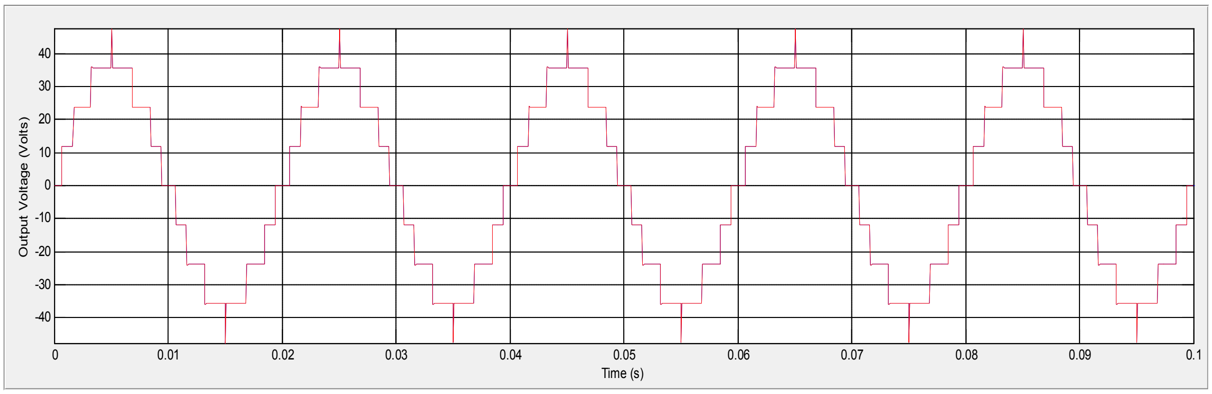


Figure 6(b)

Figure 6(a) Harmonic Spectrum 6(b) Output Volage waveform of 9 Level MLI for MI of 0.6

The THD values for varying MI along with the target lower order harmonic contents are tabulated in Table 4. The THD is found to be high for lower modulation index of 0.4 and it decreases with increasing MI. It is clearly visible that the THD consistently decreases with the increasing modulation index when compared with seven level MLI and also the lower order harmonic content is found to be negligible.

Table 4: Lower order harmonic content and THD for varying MI- 9 Level MLI

Modulation Index	Target lower order harmonics			THD (%)	Fundamental Voltage V1(Peak value in volts)	
	h5 (%)	h7 (%)	h11 (%)		Theoretical	Simulation
0.4	1.81	0.83	2.82	48.74	24.44	24.17
0.5	0.84	0.71	0.78	42.37	30.55	30.52
0.6	0.68	0.26	0.00	12.88	36.65	36.61
0.7	0.01	0.26	0.25	16.73	42.77	42.55
0.8	0.37	0.01	0.37	**9.68**	48.88	**48.54**

From the above table it is found that the fundamental peak value from the simulation is same as theoretical value which confirms the effectiveness of the proposed technique. It is also clear that the proposed FA not only gives best solution and retains consistency even for higher level MLI

Experimental Result:

To verify the performance of the proposed algorithm hardware setup is built for cascaded MLI as shown in fig. . For seven level Cascaded MLI, three Insulated gate Bipolar Transistor (IGBT) modules whereas for nine levels four IGBTs are used as H Bridges. Equal DC link voltages of 12 volts are given to all H bridges. The optimum switching angles obtained from improved FA Algorithm are loaded in FPGA Spartan 6A DSP for the modulation index of 0.8 and 0.6 and the gate pulses are generated for nine and seven level inverter. The output voltage wave form, THD and Harmonic Spectrum are shown in fig.7-10 for all the four cases. Hence the experimental output confirms the validity of the simulation results.

Figure.7 Experimental Setup of Proposed work

Case 1: Seven Level MLI: The first experiment is done with 7 level MLI for the same MI values used in simulation. The corresponding output voltage waveforms and the FFT analysis are shown in Fig.8

Figure.8(a)

	Element 1	Element 2	Element 3	Element 4	Element 5	Element 6
Urms [V]	23.564	0.0276	0.000	0.000	0.000	0.0232
Irms [A]	0.0000	0.0000	0.0000	0.000	0.0000	0.0000
P [W]	-0.000	-0.0000	-0.000	-0.00	-0.00	0.0000
S [VA]	0.000	0.0000	0.000	0.00	0.00	0.0000
Q [var]	0.000	0.0000	0.000	0.00	0.00	0.0000
λ [ ]	Error	Error	Error	Error	Error	Error
S [VA]	0.000	0.0000	0.000	0.00	0.00	0.0000
Uthd [%]	12.553	80.302	92.309	97.072	99.535	99.818
Ithd [%]	99.908	99.999	100.000	99.788	99.928	99.985

Figure.8(b)

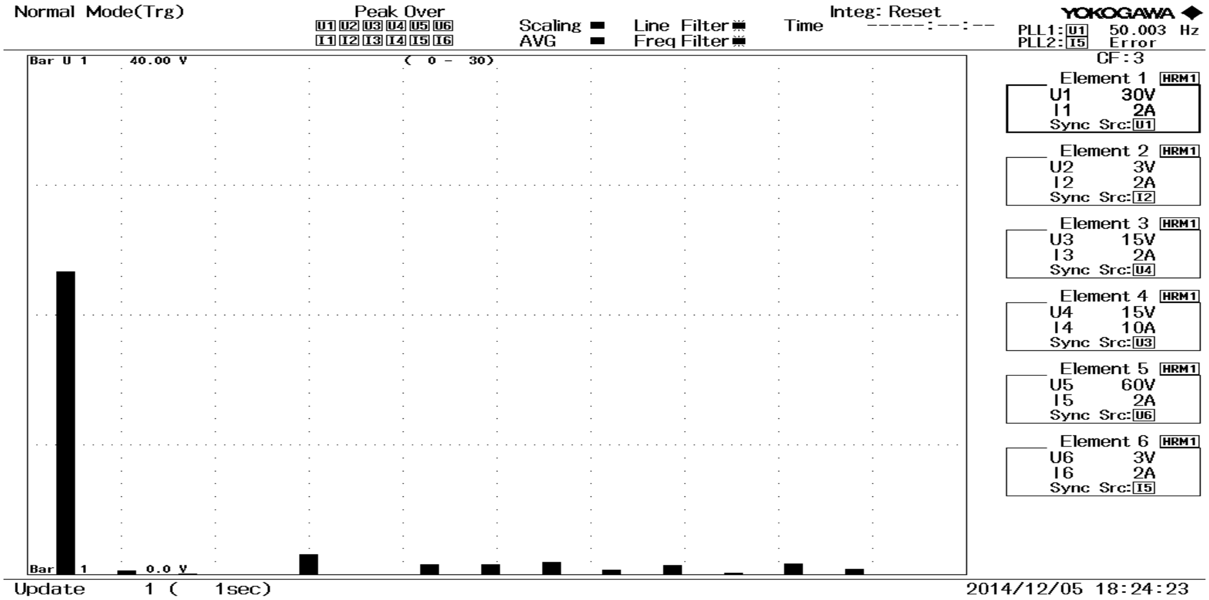


Figure. 8(c)

Figure 8(a) Output Voltage waveform 8(b) THD 8(c) Harmonic Spectrum of 7 Level MLI for MI of 0.8

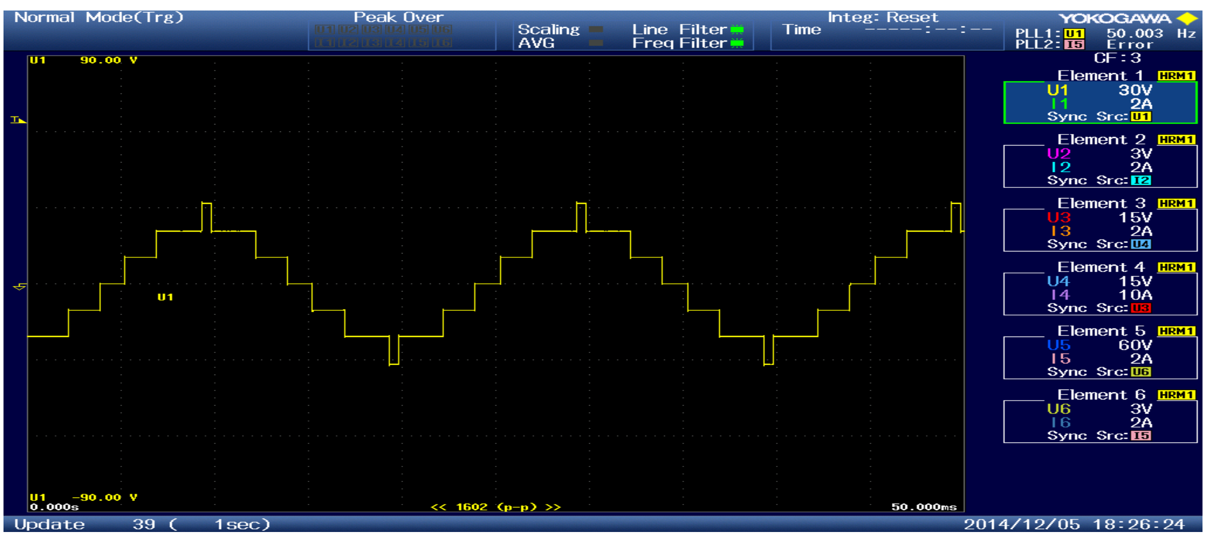


Figure.9(a)

Figure.9(b)

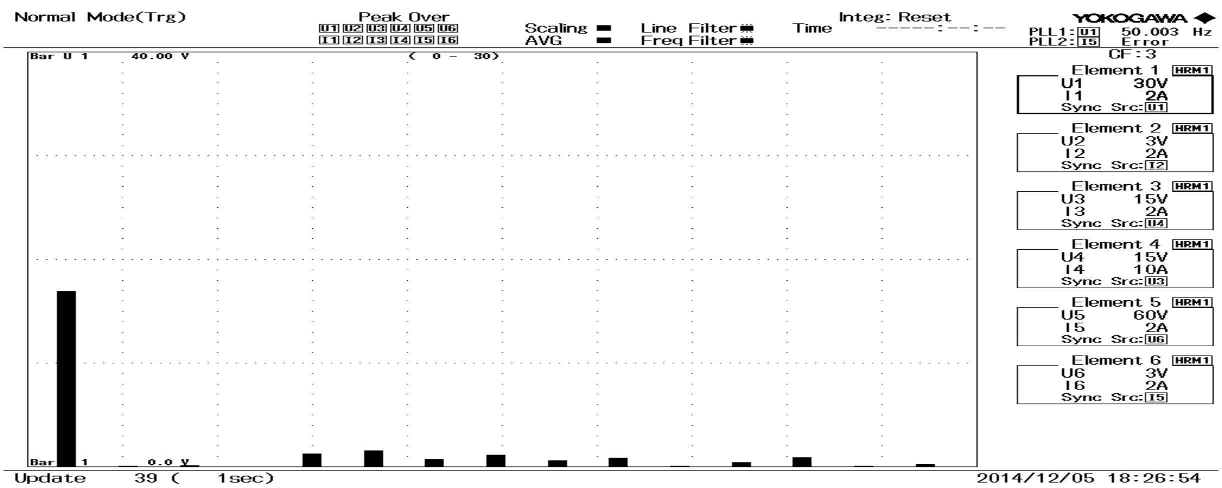


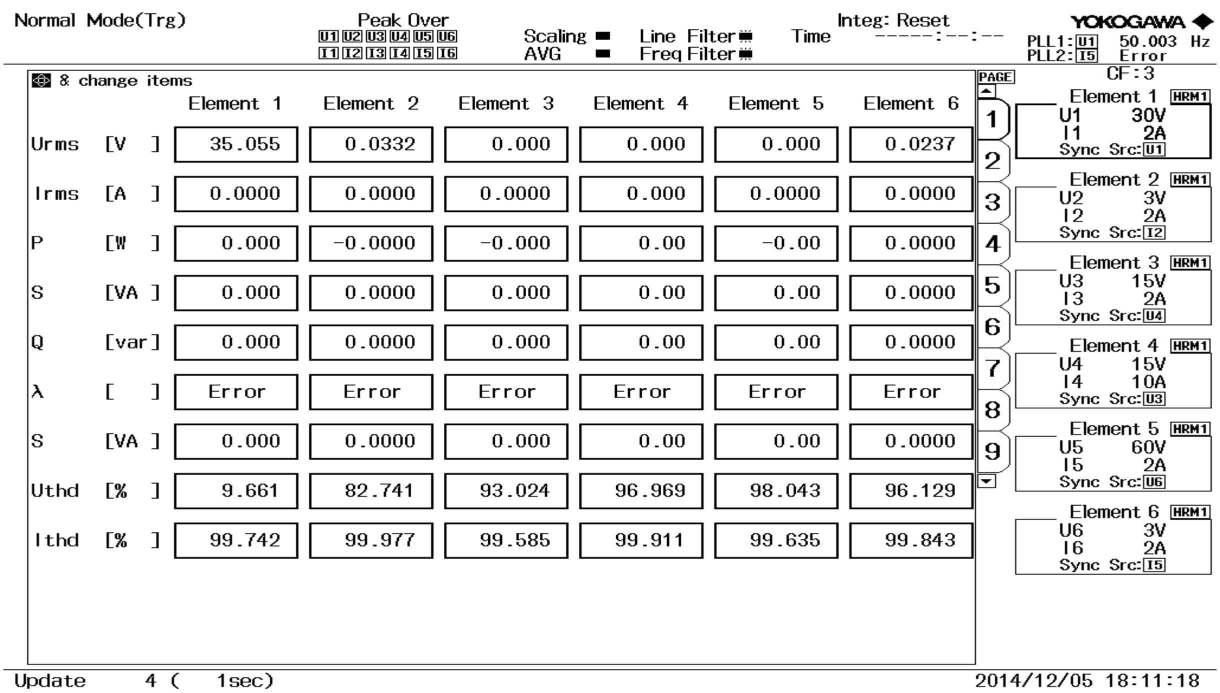
Figure. 9(c)

Figure 9(a) Output Volage waveform 9(b) THD 9(c) Harmonic Spectrum of 7 Level MLI for MI of 0.6

From the FFT analysis the 5th and 7th order harmonics are completely eliminated from the output phase voltage of the inverter.

Case 2: Nine level MLI

Figure.10(a)



		Element 1	Element 2	Element 3	Element 4	Element 5	Element 6
Urms	[V]	35.055	0.0332	0.000	0.000	0.000	0.0237
Irms	[A]	0.0000	0.0000	0.0000	0.000	0.0000	0.0000
P	[W]	0.000	-0.0000	-0.000	0.00	-0.00	0.0000
S	[VA]	0.000	0.0000	0.000	0.00	0.00	0.0000
Q	[var]	0.000	0.0000	0.000	0.00	0.00	0.0000
λ	[ ]	Error	Error	Error	Error	Error	Error
S	[VA]	0.000	0.0000	0.000	0.00	0.00	0.0000
Uthd	[%]	9.661	82.741	93.024	96.969	98.043	96.129
Ithd	[%]	99.742	99.977	99.585	99.911	99.635	99.843

Figure.10(b)

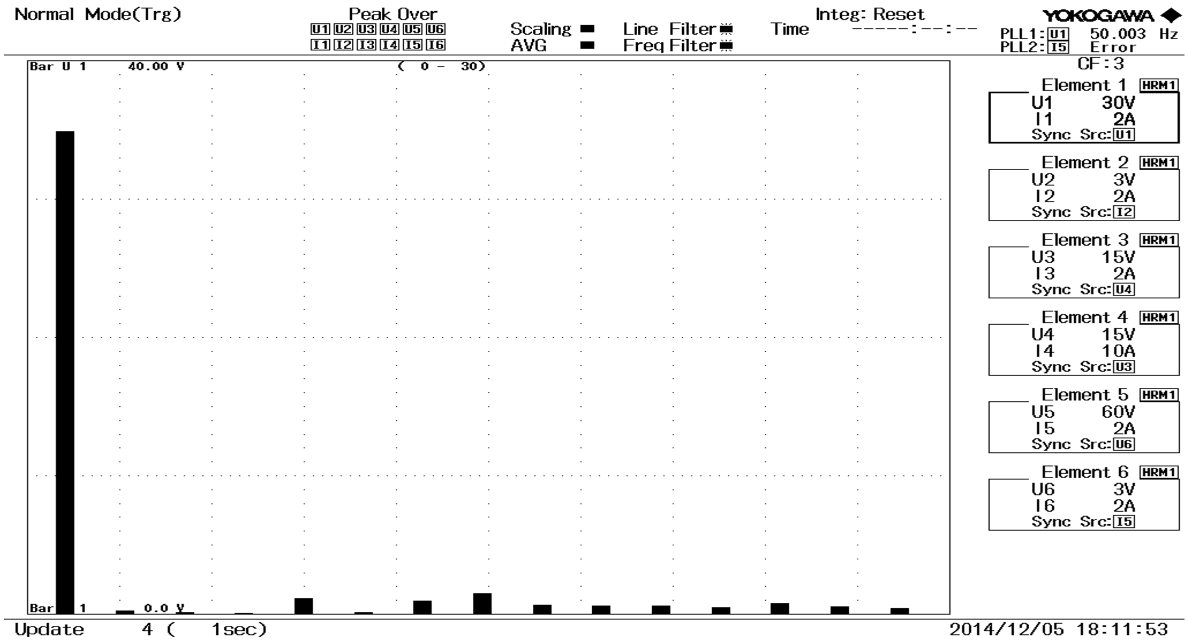


Figure. 10(c)

Figure 10(a) Output Volage waveform 10(b) THD 10(c) Harmonic Spectrum of 9 Level MLI for MI of 0.8

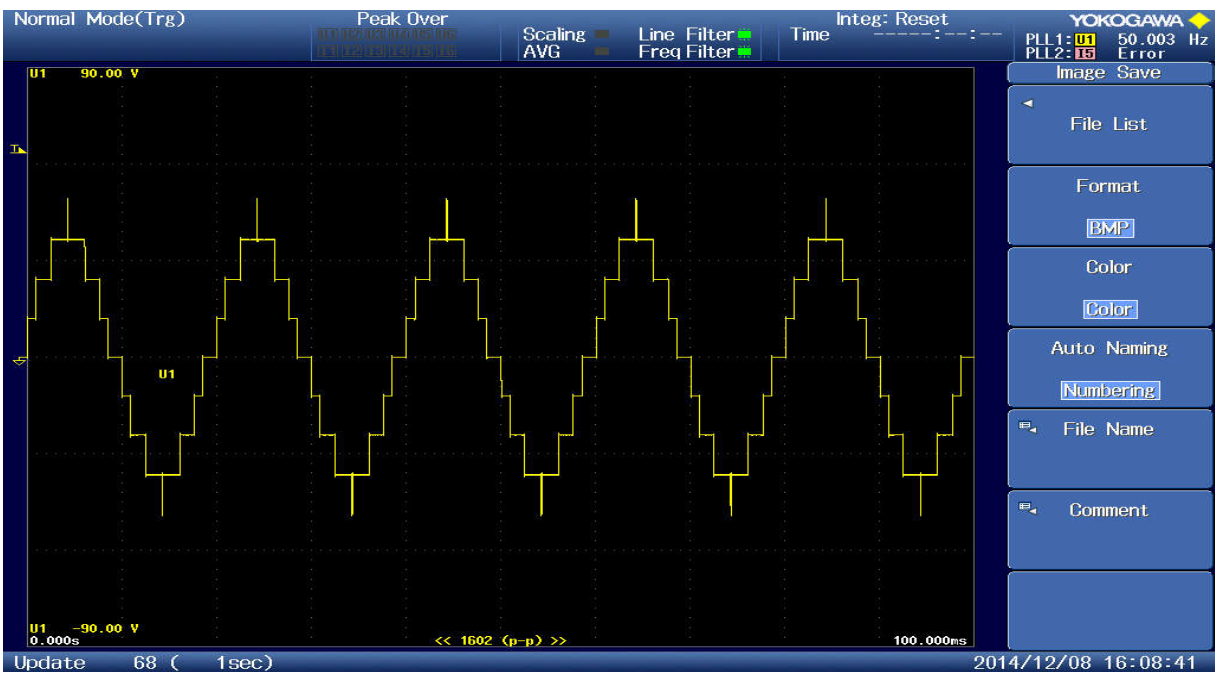


Figure.11(a)

Figure.11(b)

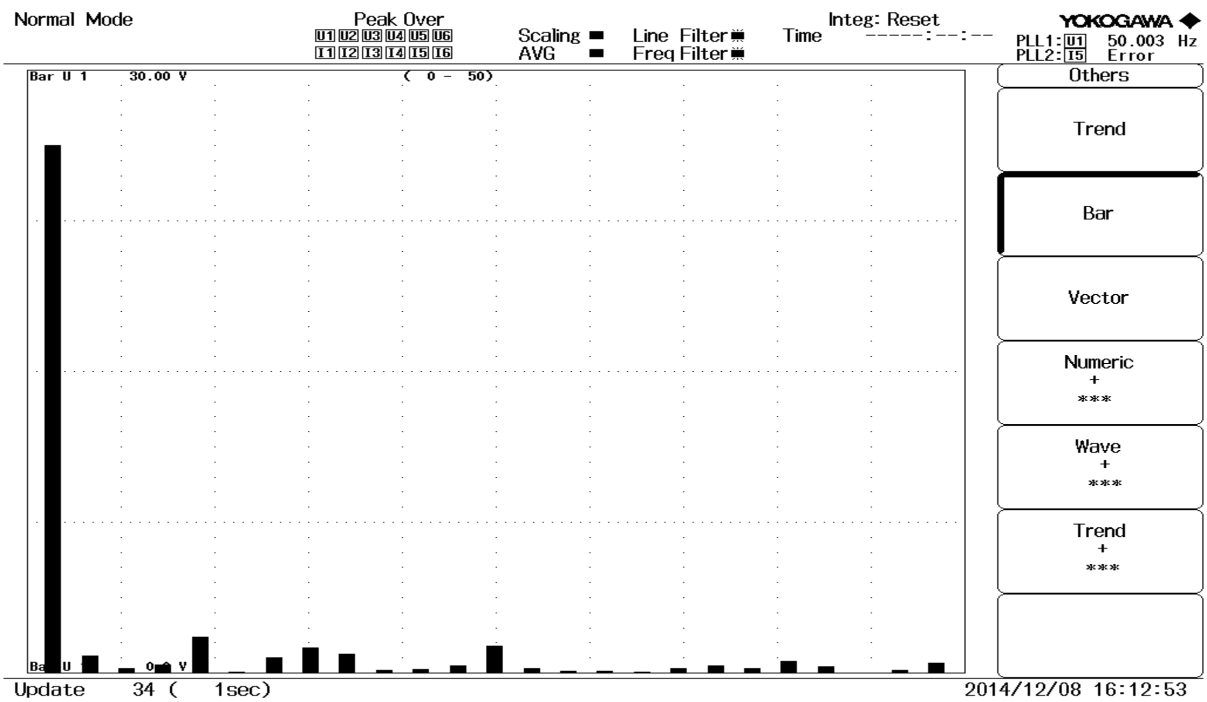


Figure.11(c)

Fig 11(a) Output Volage waveform 11(b) THD 11(c) Harmonic Spectrum of nine Level MLI for MI of 0.6 From the FFT analysis it is shown that the 5th, 7th & 11th order harmonics are completely eliminated from the output phase voltage of the inverter.

Table 6: Performance Comparison

Level	Modulation Index (MI)	THD (%)	
		Simulation	Experiment
Seven	0.6	18.51	18.581
	0.8	12.55	12.553
Nine	0.6	12.88	12.908
	0.8	9.68	9.66

From Table 6 it is confirmed that the experimental results validate the simulation results. When compared with other heuristic methods it is found that FA yields best solution in every independent trial and also fewer parameters are to be tuned. Also the concept of FA is simple to understand , requires simple coding, easy implementation in Matlab and also takes least computation time of 1.7 with 3GHz clock frequency . Hence FA is suggested for Fundamental frequency modulation in real time applications.

Conclusion

A novel methodology for the estimation of the optimum switching angles of a nine and seven level cascaded H bridge inverter with equal DC sources using improved Firefly Algorithm is proposed in this work. This algorithm is developed using MATLAB software and the nine and seven level CHB MLI have been implemented for the optimal switching angles obtained from SAMFA using MATLAB SIMULINK environment. It has been demonstrated that the target lower order harmonics have been well mitigated. The results revealed that the Firefly Algorithm adopted in this application is competitive to other popular optimization techniques with some additional advantages like least computation time, fast convergence, more probable to attain optimal solution and easy implementation in MATLAB. Further the hardware is built for 9 and 7 level cascaded MLI and gating pulses are generated using FPGA Spartan 6A and the harmonic spectrum analysis are made. The experimental output confirms the validity of the simulation results.

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