REAL TIME IMPLEMENTATION OF SELECTIVE HARMONIC ELIMINATION OF MULTILEVEL INVERTER WITH NON EQUAL AND TIME VARYING DC SOURCES USING ARTIFICIAL NEURAL NETWORK

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Abstract. Estimation of the switching angles of the levels of the step modulated multi level inverter in the context of selective harmonic elimination is a difficult task as it involves solving a set of trigonometric transcendental equations. Though a number of optimisation techniques are available for numerically solving the trigonometric transcendental equations, the real time estimation of the switching angles using the optimisation techniques, when implemented in a digital processor involves a large number of floating point operations (FLOPS) which makes it practically unsuitable for real time applications. In this paper the design and implementation of a nine level inverter is presented with four cascaded H bridge units powered by four isolated DC voltage sources, the terminal voltages of which may vary from their nominal values unpredictably from time to time. The four switching instants required for the nine level inverter are estimated online using an Artificial Neural Network (ANN) realised in a micro controller. A set of 256 solution vectors corresponding to 256 input conditions are derived offline, using the Particle Swarm Optimisation (PSO) technique. This data set comprising of the 256 combinations of the input voltages and the corresponding solution vectors are used to train the ANN beforehand and the trained ANN was then embedded in the micro controller. The proposed methodology was verified in the MATLAB SIMULINK environment. An experimental setup, using the ARM processor Phillips LPC 2148 that features multitasking facility, is constructed and the proposed method is practically realised and the results validate the proposed technique.

Keywords: *Cascaded H Bridge inverters, Selective Harmonic Elimination, PSO, Artificial Neural Network*

I INTRODUCTION

Multi level inverters are used for medium, high voltage and high power requirements. Multilevel inverters offer improved power quality and also design flexibility in designing with components of lower voltage ratings to handle or produce higher voltage levels and hence higher power levels [1]. The diode clamped, the flying capacitor and the cascaded multi level inverters are some popular multi level inverter configurations. If a multi-level inverter is opted for, but what is available is just a single DC source then the diode clamped or the flying capacitor type multi level inverter configuration can be used [2]. However if the number of available 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[3].

Further, the cascaded multilevel inverters can be categorised as high and low switching frequency operated models. The high switching frequency model of multilevel inverters use a large number of sub switching in each level and thus the harmonic contents of the AC output of the inverter are pushed beyond the switching frequency, thus lowering the THD of the output AC waveform of the voltage source inverter. However, while the increased switching frequency improves the quality of the output waveform, the price is paid in terms of increased switching losses. Renewable energy sources like solar power, fuel cell or small wind generators where the output is DC, can be integrated into multi level inverters of medium output voltage and can be used to directly drive loads like pumping systems operated by induction motors. In such applications, where the DC sources are derived from a set of medium power generators like solar panel, the switching losses become an overhead and high switching frequency operation will not be justified.

Step modulated low switching frequency inverters are suitable for constructing multi level inverters with small DC power sources. With step modulation the advantage is that by appropriately placing each level over the other at appropriately calculated timings we can eliminate a certain number of harmonics [4,5,6,]. If there are n levels above the time axis then n-1 harmonics can be eliminated. The angles or timings as measured from the Y axis, at which the various levels of a multilevel inverter can be positioned one above the other, should be appropriately calculated by solving a set of equations called SHE equations. In all the above cases the henceforth untold assumption is that by the DC voltage sources offer a steady DC voltage throughout the operation of the inverter. The case of a multi level inverter where there are n levels above the time axis, can be defined by a set of n equations and solving these n equations give n angles and when implemented these n angles guarantee the required amplitude of fundamental and n-1 harmonics are removed. The concept of the selective harmonic elimination is that when the selected, usually the lower order, harmonics are eliminated from the output voltage waveform of a voltage source inverter, then the task of removing the higher order harmonics can be easily carried out by the use of passive filters or by the load itself if the load is of low pass nature like induction motor etc.

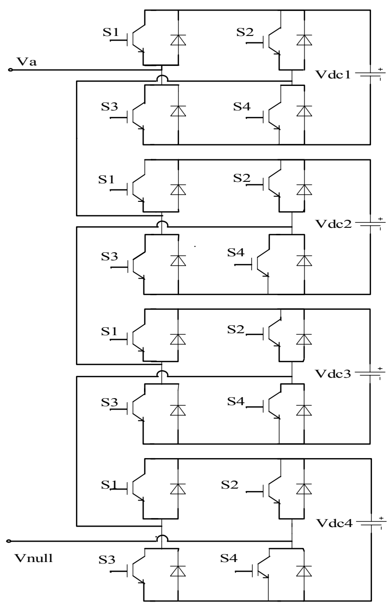

Figure 1: Structure of nine level cascaded H Bridge multilevel inverter

Selective harmonic elimination as applied to multilevel inverters is reported in large volumes of literature. The switching angles can be found by solving the set of SHE equations. There are two approaches for arriving at the switching angles embedded in the SHE equations. Classical methods like Newton Raphson, Resultant theory [7, 8] and Heuristic methods like Genetic Algorithm [9, 10] and Particle swarm optimization (PSO) [13] were reported widely in the literature.

Cascaded multi level inverters with equal voltage levels of the DC sources are known as the 'symmetrical' DC sources. Asymmetrically sourced multi level cascaded inverters are also reported in the literature [13, 14, 15]. The use of asymmetrical DC voltages of the different sources can reduce the number of switches required for the same levels of output as compared to the case of the symmetrical voltages scheme. For example two equipotent dc sources can be used to form a five level single phase inverter with 8 switches arranged in two cascaded H bridge configuration. But with asymmetrical DC voltage levels, in 1:3 order, a multi-level single phase inverter of nine levels can be achieved. However when the sources are from the renewable energy category like solar panels or wind sources then the chances are that the DC voltage levels of the sources are not constants. Fuzzy logic controller used for elimination of the low order harmonics and achieving the desired fundamental output voltage in multilevel inverter for photo voltaic system is proposed in [16]. In [11,12] the authors have presented the methodology and the design of selective harmonic elimination as applied to a single phase 11 level inverter using Genetic Algorithm and ANN combination for varying sources.

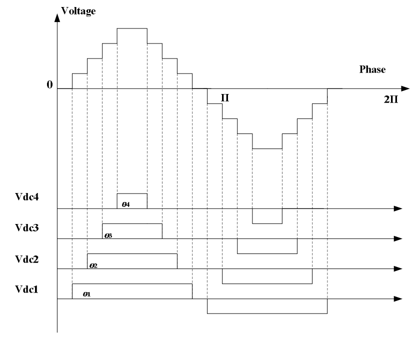

Figure. 2. Output voltage waveform of a 9-level Cascade multilevel inverter

The strategy to be adopted under time varying DC source voltage conditions is quite similar to the case of fixed DC voltage sources with just a slight variation in the formation of the set of SHE equations. In the case of symmetrical DC voltages based multilevel inverter, the SHE equations can be easily normalised and viewed as if they are independent of the source voltages. However in the case of variable voltage DC sources the different DC voltage levels or atleast the factors by which each voltage level differs from the nominal voltage levels are also included in the SHE equations to be solved. An appropriate fitness function is adopted and this function includes the factor by which each voltage level differs from the nominal DC voltage level. The variations of the source voltages may occur unpredictably and as such a real time manipulating system is needed that can find out the switching instants in the face of varying DC source voltage levels.

In this paper a nine level inverter with four cascaded H bridge modules will be discussed. The structure of nine level cascaded H bridge inverter and its output voltage waveform are shown in Figure 1 & 2 respectively. The strategy adopted is that the variable DC voltages are monitored and the switching instants are estimated as one task in an ARM processor. Simultaneously as the other parallel task in a multi-tasking environment of the ARM 7 LPC2148 processor the PWM is generated uninterruptedly. Every time there is a change in the source voltage occurs new switching instants are estimated. The methodology adopted for the estimation of the switching instants involves two phases. One is an off line phase wherein a PSO program is used to estimate the switching instants for various possible DC voltage combinations. The optimum switching angles obtained offline from PSO are used as the training data for an ANN. In the second phase which is the real time phase, this trained ANN is used for estimating the switching instants under varying DC voltage levels that change in real time. The high clock frequency of 100 MHz operation of the ARM processor guarantees seamless operation.

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 fundamental voltage for the available DC voltage levels of the isolated DC sources with the selected lower order harmonics eliminated irrespective of differences in the magnitude of the individual DC source voltages with respect to the nominal DC voltage level of each source.

After the introduction in chapter I the rest of the paper is arranged as follows. Chapter II gives a brief introduction to SHE PWM as applied to multi level inverters using step modulation. Chapter III gives the details of how the PSO is employed to handle the problem at hand with an insight into the implementation of a trained ANN in the ARM processor. Chapter IV discusses the results of simulation and chapter V discusses the experimental verification followed by the outline for future research given in the conclusion.

II Mechanism of SHE PWM in Step Modulated Inverter

The single pulse modulated full bridge inverter output is a square wave with quarter wave symmetry. The spectrum of the quarter wave symmetrical wave consists of the fundamental sinusoidal wave at the switching frequency of the single pulse inverter and all the odd harmonics with respect to the fundamental. The magnitude of the fundamental can be controlled by adjusting the width of the single pulse as shown in the Eq. (1).

$$V_{fund} = \frac{4V_{dc}M}{\pi} \qquad (1)$$

Where M is the modulation index

Elimination of the lower order harmonics does not immediately lead to the overall improvement of quality of the output voltage wave of the inverter. It basically pushes out the energy content in these harmonics towards the higher order harmonics. Therefore the THD of the SHE PWM based inverter output voltage will be high until the higher order harmonics are also eliminated by filtering them out using passive filters.

In order to improve the quality of the output voltage waveform of a voltage source inverter the other option is to use multi level inverters. While it facilitates the usage of low voltage devices for high voltage applications, the multilevel inverters can also help to improve the quality of the output voltage wave form in terms of decreased THD or in other words a wave closer to a sine wave. The multilevel inverter can integrate a number of isolated DC power sources to render a scaled up AC voltage output. If the spectrum of the single pulse width modulated output voltage waveform is considered, the harmonics are of different amplitudes but their phase shift is just positive or negative 180 degrees with respect to the fundamental. If the pulse width is changed, only the amplitude of the fundamental is changed while the amplitude and also the phase of all the harmonics are changed. Thus if a number of single pulse width modulated waves are cascaded with each level positioned over the other at appropriate positions then by virtue of this directional aspect of the harmonics, the effect of any particular harmonic of one level can be cancelled out by the same order of harmonics in the next higher level of the inverter. This phenomenon is explained by considering the following case,

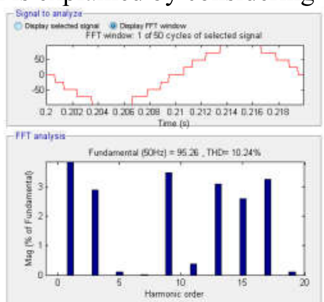

Figure. 3. SHE methodology

Here 5th, 7th, 11th harmonics are eliminated.

$$H_n(\theta) = \frac{4V}{n\pi} \sum_{j=1}^{s-1} \cos(n\theta_j) \quad (2)$$

for all odd n

$H_n(\theta) = 0$, for all even n (3)

where,

H_n is the amplitude of the harmonics.

s is the number of levels

n is an odd harmonic order

θ_j is the j^{th} switching angle

V is the amplitude of voltage levels

For 5th harmonic,

s=1, $H_5(\theta_1) = 3.709\angle 175.5^o$

s=2, $H_5(\theta_2) = 2.068\angle -4.41°$

s=3, $H_5(\theta_3) = 5.429\angle -4.41^0$

s=4, $H_5(\theta_4) = 3.696\angle 175.5^o$

Therefore, the 5th harmonic is eliminated with respect to fundamental as follows.

$H_5(\theta) = 0.3363\angle 180^0$

For 7th harmonic,

s=1, $H_7(\theta_1) = 1.291\angle 173.7^0$

s=2, $H_7(\theta_2) = 3.854\angle -6.174^0$

s=3, $H_7(\theta_3) = 1.222\angle 173.7^0$

s=4, $H_7(\theta_4) = 1.35\angle 173.7^o$

Therefore, the 7th harmonic is eliminated with respect to fundamental.

$H_7(\theta) = 0.011\angle 128^0$

In a multilevel inverter if driven by different voltage sources, 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 voltage are given.

The working strategy

When there are a number of 'n' isolated DC voltage sources feeding 'n' number of H bridge inverter units then these 'n' voltage sources are included in the derivation of the switching angles. If these voltage sources are held constants then for any particular modulation index the switching angles of all the levels will also be constants as long as the modulation index is constant. In situations like varying voltage sources, the problem becomes little different and the instantaneous output voltage of the inverter becomes,

$$V(wt) = \sum_{(n=1,3,5...)} 4V_{dc}/n\pi \,(k1\cos(n\theta_1) + k2\cos(n\theta_2) + k3\cos(n\theta_3) + \ldots + k_s\cos(n\theta_s))\sin(nwt) \quad (4)$$

In the case of a nine level inverter there are four H-Bridges individually powered by four separate DC sources and these DC sources are of voltage V_{dc} as the nominal DC voltage and k_1, k_2, k_3 and k_4 are the factors by which these voltages differ from the nominal value. $\theta_1, \theta_2, \theta_3, \theta_4$ are the step angles. The SHE equation for such a system will be as follows.

$$\left.\begin{array}{l} k_1\cos(\theta_1)+k_2\cos(\theta_2)+k_3\cos(\theta_3)+k_4\cos(\theta_4)=SM \\ k_1\cos(5\theta_1)+k_2\cos(5\theta_2)+k_3\cos(5\theta_3)+k_4\cos(5\theta_4)=0 \\ k_1\cos(7\theta_1)+k_2\cos(7\theta_2)+k_3\cos(7\theta_3)+k_4\cos(7\theta_4)=0 \\ k_1\cos(11\theta_1)+k_2\cos(11\theta_2)+k_3\cos(11\theta_3)+k_4\cos(11\theta_4)=0 \end{array}\right\} \quad 5)$$

Where S is the number of H Bridges and M is the modulation index. With respect to the set of SHE equations shown in Equation (5), it is clear that in order that the 5th, 7th and the 11th order harmonics are eliminated or minimised and that the fundamental voltage is fixed at the required level.

The fitness function is set to minimize the summation of the individual absolute errors (AE).

$$FF{=}{=}100*\frac{(V1d-V1)^4}{V1d^4}+\left(\frac{50}{V1}\right)^2*\left\{\left(\frac{V5}{5}\right)^2+\left(\frac{V7}{7}\right)^2+\left(\frac{V11}{11}\right)^2\right\} \quad (6)$$

where, *V1* is the fundamental voltage component.

It is assumed that the nominal voltage of each DC source is 24 volts. These voltages may come down as low as 6 volts and may shoot up as high as 24 volts. Between the extremes of 6V and 24V two more levels are considered and they are 12V and 18V. Considering the four sources and considering the four variations we can form 256 combinations. For all these combinations for a modulation index of 1 the switching instants are found using the PSO. It is assumed, considering the practical necessity that only the maximum possible fundamental voltage is to be derived and hence the modulation index will always be 1. With variable DC voltage sources varying between 6V to 24 volts it is not possible to get any fixed amplitude for the fundamental output voltage.

III PARTICLE SWARM OPTIMISATION

Particle Swarm Optimisation is a heuristic optimisation technique that is inspired by the cooperative social behaviour of Flocks of birds or Schools of fish. They are characterised by the observation that whenever there is a common objective each member of the community comes out with a suggestion for solution. These suggestions of the individuals are used individually to estimate the effectiveness of the corresponding solution based on the suggestions of each of the individual and the distance of the individual solutions to the expected overall solution of the problem at hand are measured.

Some of the members of the community might have suggested solutions which may be closer to the expected one while others may be far away. The process is repeated and each individual comes out with a new suggestion after properly correcting the previous suggestion based on the suggestion of the globally best suggestion and the best of the past suggestions of the individuals. Continuing in this manner each of the individuals correct their suggestions again and again until all the members come out with the same suggestion that best suits the situation or problem at hand. Depending upon the problem all the members might be required to come out with a solution set or solution vector consisting of a fixed number of elements. The equations below describe the PSO situations.

The particle changes its position based on the velocity and position update equations according to *pbest* and *gbest* as given in Eq. (7).

$$v_i^{t+1} = \omega \times v_i^t + C_1 \times r_1 \times (pbest_i^t - x_i^t) + C_2 \times r_2 \times (gbest_i^t - x_i^t) \quad (7)$$

$$x_i^{t+1} = v_i^{t+1} + x_i^t \quad (8)$$

where,

ω is the inertia weight.

v_i^t is the velocity of the i^{th} particle.

C_1 is the cognitive factor and C_2 is the social factor.

r_1 and r_2 are the random numbers with range [0,1].

$pbest_i^t$ is the best solution of the i^{th} particle.

$gbest_i^t$ is the best solution among all particles in a swarm.

x_i^t is the particle position at t^{th} iteration.

x_i^{t+1} is the updated particle's position.

v_i^{t+1} is the updated particle's velocity

Application of PSO for the proposed work

As for the SHE problem, associated with the nine level inverter the solution set of the individuals of the swarm will be a vector of four elements $\theta_1, \theta_2, \theta_3, \theta_4$ .All the four elements of the solution vector corresponding to all the members of the swarm are first initialised with random values in the expected range of solution that is between 0 and π/2 viz. θ_{1i}, θ_{2i}, θ_{3i} and θ_{4i} where i is the swarm member index. The position of each swarm is described by this vector. The vector of randomised elements of all the swarm members will be used in the fitness function and the fitness of each swarm is found. Some of the members may be more close to the final solution and some may be very far. Based on the value of the fitness function pertaining to the individual members the best member is identified. Each particle then adjusts its position by adjusting its solution vector. All the elements of the vector are corrected with a quantity called velocity and each particle of the swarm now moves on to a new position.

Usually in a random search problem the search period is increased if the numbers of constraints are large. The usually laid down condition that $\theta_1<\theta_2<\theta_3<\theta_4$ is relaxed in this design. It is enough that every solution is acceptable if it just satisfies the SHE equations. Even if the angles are not obtained in the descending order such solutions are still useful because in a series connected H bridge inverter string the bridges can be activated in any order by the micro controller. Therefore if it turns out that $\theta_2<\theta_1$ then the sequence can be automatically taken care of by the micro controller and the second bridge comes into action before the first one. Relaxing the condition of ascendency of angles reduces the search time and it is especially useful when we have to find out 256 sets of solutions using the PSO in offline state. Optimum solutions (switching angles) obtained from the PSO for 10 cases are given in Table 1.

Table 1.Switching angles obtained from PSO

Case	K1	K2	K3	K4	$\boldsymbol{\theta_1}$	$\boldsymbol{\theta_2}$	$\boldsymbol{\theta_3}$	$\boldsymbol{\theta_4}$
					In radians			
1	0.25	0.25	0.25	0.25	0.061	0.347	0.581	1.544
2	0.2	0.2	1.0	0.2	0.2	0.6	0.93	1.41

	5	5	0	5	41	17	9	5
3	0.50	0.75	1.00	1.00	0.107	0.461	0.957	1.571
4	0.50	0.25	1.00	0.50	0.402	0.766	1.025	1.571
5	0.50	0.50	0.50	0.50	0.00	0.303	0.497	1.028
6	0.75	0.25	0.25	1.00	0.228	0.529	0.956	1.571
7	0.75	0.75	0.75	0.75	0.103	0.617	0.752	1.382
8	1.00	0.5	0.25	0.75	0.222	0.453	0.992	1.066
9	1.00	0.75	0.25	0.75	0.21	0.682	0.74	1.221
10	1.00	1.00	1.00	1.00	0.175	0.386	0.711	1.078

Application of ANN to nine Level MLI

The ANN unit is a three layer, feed forward back propagation network consisting of four neurons in the input and the output layers with only one hidden layer with 10 neurons in the hidden layer.While the neurons in the input layer and the hidden layers are of the sigmoidal type, the neurons in the output layer are of the linear type with upper value limited to π/2 and the lower value limited to 0.Since the training data is quite big and it encompasses the entire possible range, the solutions for other combinations not derived from the PSO can be practically precisely interpolated by the ANN. Also all practically possible combinations of input voltages will lie very closely to the training data set.

The structure of the ANN is shown in Figure 4.

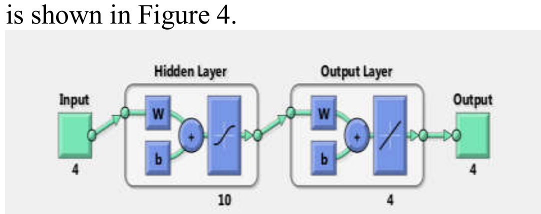

Figure 4. Structure of ANN for the proposed work

It is assumed that the voltage levels of the four DC voltage sources may swing and lie anywhere between 6V and 24 volts. Since the nominal voltage level is considered to be 24V the factor by which the DC voltage sources can vary will lie in the range 0.25 corresponding to 6V and 1 corresponding to 24V. The possible combination of input voltages will be all values between 6 6 6 6 and 24 24 24 24. If incremented from 6 6 6 6 towards 24 24 24 24 in discrete steps of 6 then there are 256 combinations. These combinations will produce different total V_{dc} and hence different V_{fund} of the AC output.

For each combination of input voltages, PSO is run for 100 iterations and the optimum solution is found & it is repeated for entire 256 combinations. This is just a single time offline activity. For ANN the input vector consists of four neurons which are the DC voltages. The output layer consists of four neurons which are the four switching angles. This set of data having a one to one input output mapping can be used to train an Artificial Neural network with four neurons in the input layer and four neurons in the output layer with one hidden layer. For the proposed work 10 neurons in the hidden layer is found to be optimal.

RESULTS AND DISCUSSION

The MATLAB/ SIMULINK model of the proposed system is as shown in Figureure 5. The model is a nine level single phase inverter with four cascaded H bridges. The system uses four isolated

DC voltage sources and the voltage levels of each source can be changed. There are three basic sub systems used in the model. The first is the main unit consisting of the power topology with the four cascaded H bridge inverter units with four MOSFETs in each unit. The second subsystem consists of the ANN that reads the four input voltages and produces the four switching angles or step angles. The third sub system called the switching sub system that translates the switching angles into pulses produced at appropriate instants. These pulses reach the gates of the MOSFETs.

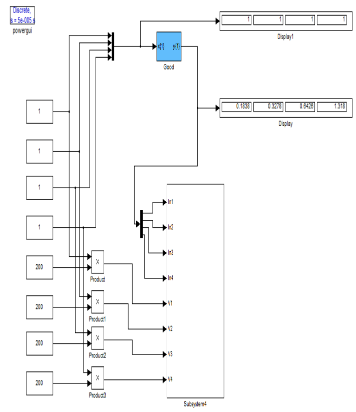

Figure. 5. Simulink model of the proposed work

Figures. 6(a) - 6(g) shows the output voltage waveform and the corresponding Fast Fourier Transformation indicating the elimination of the selected harmonics. Various voltage combinations give different fundamental voltages with a modulation index of 1 and the values obtained are in conformity with the applicable mathematical relationship. It is given in Table 2 and Table 3

Table 2 Switching angles obtained from ANN

Case	K1	K2	K3	K4	$\boldsymbol{\theta}_1$	$\boldsymbol{\theta}_2$	$\boldsymbol{\theta}_3$	$\boldsymbol{\theta}_4$
					In radians			
1	0.25	0.50	0.50	0.25	0.137	0.171	0.437	0.702
2	0.75	1.00	1.00	0.25	0.083	0.223	0.434	0.663
3	0.75	0.50	1.00	1.00	0.114	0.192	0.343	0.758
4	0.75	1.00	0.50	1.00	0.083	0.223	0.434	0.663
5	0.50	0.75	0.50	0.75	0.121	0.226	0.364	0.577
6	0.50	0.50	0.50	0.50	0.156	0.203	0.514	0.682
7	0.75	0.75	0.75	0.75	0.109	0.291	0.355	0.752

Table 3 H Bridge Voltages and its Fundamental Voltage with Harmonics in %

Case	V1	V2	V3	V4	V_{fund} (Volts)	Harmonics %			THD %
						5^{th}	7^{th}	11^{th}	
1	6	12	12	6	42.04	0.37	1.03	0.227	18.53
2	18	24	24	6	81.25	2.81	1.31	0.19	13.71
3	18	12	24	24	88	0.01	2.35	4.45	14.75
4	18	24	12	24	89.78	1.04	0.29	0.43	15.78

5	12	18	12	18	70.45	1.07	3.59	0.09	18.47
6	12	12	12	12	54.85	2.76	0.55	1.23	15.44
7	18	18	18	18	82.45	0.17	0.05	4.14	16.15

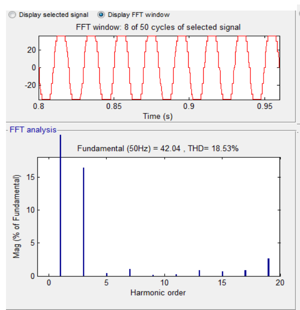

Figure. 6(a). Case 1

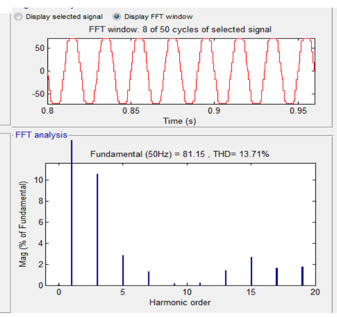

Figure. 6(b). Case 2

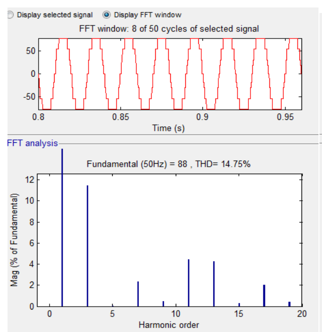

Figure. 6(C). Case 3

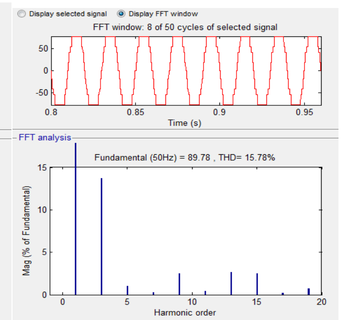

Figure. 6(d). Case 4

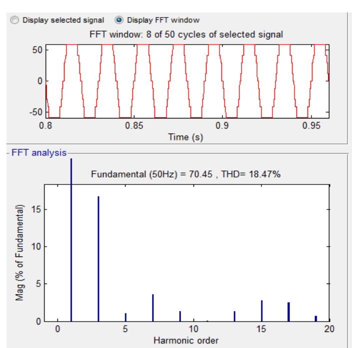

Figure. 6(e). Case 5

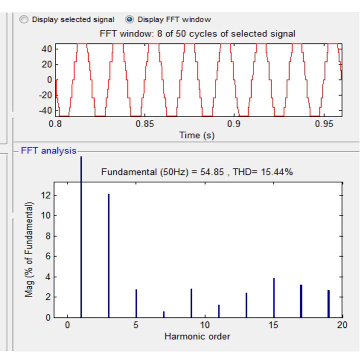

Figure 6(f). Case 6

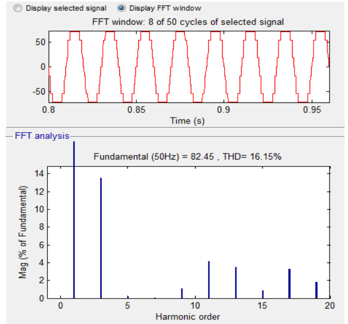

Figure 6(g). Case 7

The waveforms and FFT corresponding to the case of switching instants with $\theta_1 > \theta_2$ and also a case where
$\theta_3 > \theta_4$ are also shown which confirm that the condition $\theta_1 < \theta_2 < \theta_3 < \theta_4$ is not necessarily be considered if the sequence of operation of the H bridge units can be altered according to the requirement.

In a multilevel cascaded H bridge inverter with four levels,There are four H-bridges each operated by individual DC sources V_1, V_2, V_3 and V_4. If V_1= 6 V, V_2=12 V, V_3=18 V and V_4=24 V.

Then the maximum value of the fundamental voltage at 50 Hz from each H-bridge inverter stage for modulation index M=1 will be $V_{1f} = \frac{4V_{dc}}{\pi} = \frac{4 \text{ x } 6}{\pi} = 7.6433 \text{ V}$

Similarly,

$$V_{2f} = \frac{4 \text{ x } 12}{\pi} = 15.2788 \text{V}$$

$$V_{3f} = \frac{4 \text{ x } 18}{\pi} = 22.9183 \text{V}$$

$$V_{4f} = \frac{4 \text{ x } 24}{\pi} = 30.5577 \text{V}$$

Since the H-bridges are in series and since quarter wave symmetry is maintained in all the four level, the net fundamental output voltage will be,

$$V_0 = V_{1f} + V_{2f} + V_{3f} + V_{4f}$$
$$= 7.6433 + 15.2788 + 22.9183 + 30.5577$$
$$= 76.3981 \text{ V}$$

In the same manner as demonstrated the fundamental amplitude of any combination of DC voltages can be calculated.
Six cases of arbitrary combinations of four source voltages were placed at the inputs of the Four H Bridges and the results recorded are shown in Tables 4 and 5 and the corresponding FFT are shown in Figureure 7a-7f.

Table 4.Six arbitrary combination of Normalised input voltages and the corresponding switching angles and the THD

Case	V1	V2	V3	V4	V_{fund} (Volts)	Harmonics %			THD %
						5th	7th	11th	
1	16.8	19.2	15.6	11.76	73.5	0.49	0.36	1.97	17.33
2	19.44	22.8	17.28	15.36	85.16	0.71	0.8	1.32	14.31
3	12.96	18.72	8.4	20.64	71.38	0.82	3.32	0.43	18.82
4	19.68	18.48	6.96	11.28	65.74	1.03	0.55	2.69	18.71
5	6.48	16.56	19.92	11.28	62.63	1.29	1.01	1.12	16.80
6	6.24	18.72	18.96	13.2	66.63	0.55	1.83	0.39	17.76

Table 5.Six arbitrary combination of input voltages and the corresponding Amplitudes of Fundamental and Harmonics with THD

Case	K1	K2	K3	K4	θ_1	θ_2	θ_3	θ_4	THD
					In radians				
1	0.70	0.80	0.65	0.49	0.137	0.235	0.443	0.735	17.33
2	0.81	0.95	0.72	0.64	0.109	0.253	0.516	0.779	14.31
3	0.54	0.78	0.35	0.86	0.115	0.224	0.361	0.552	18.82
4	0.82	0.77	0.29	0.47	0.116	0.331	0.352	0.718	18.71
5	0.27	0.69	0.83	0.47	0.115	0.128	0.425	0.694	16.80
6	0.26	0.78	0.79	0.55	0.099	0.165	0.378	0.648	17.76

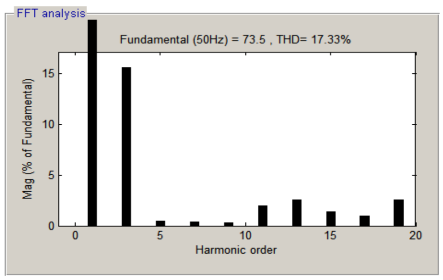

Figure.(7a).Case 1

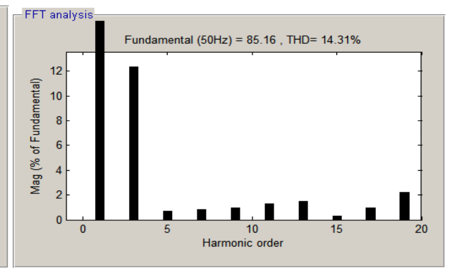

Figure.(7b).Case 2

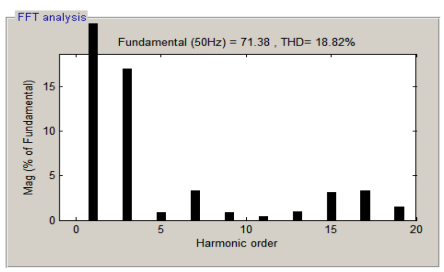

Figure.(7c).Case 3

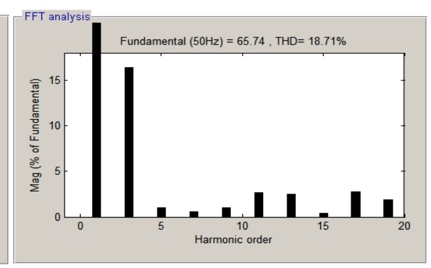

Figure.(7d).Case 4

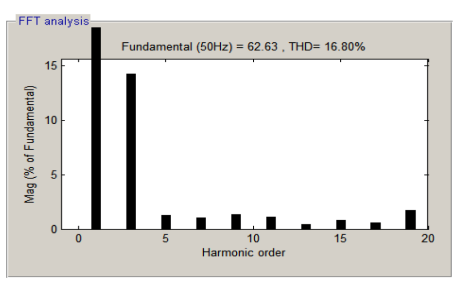

Figure.(7e).Case 5

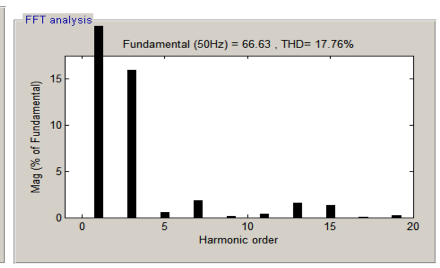

Figure.(7f).Case 6

Figure 7: FFT for the six arbitrary cases of four input voltage combinations

V HARDWARE IMPLEMENTATION AND EXPERIMENTAL RESULTS

Figure 8 show the hardware setup of the proposed work. A set of Four H bridge units have been constructed with 16 numbers of IRF840 MOSFET devices. The gates of the MOSFETs are driven through opto couplers of type MCT 2E thus providing an electrical isolation between the power circuit and the control circuit.

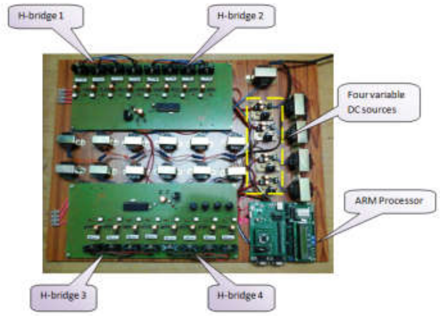

Figure.8 Experimental setup of 9 Level Inverter

In the experimental set up four variable voltage power supplies are considered as varying sources. The voltage levels of each power supply can be changed from 0 to 24. These power supply units are electrically isolated and source the individual H bridge units. The four DC voltage sources are appropriately attenuated to 0 – 3.3 scale and fed into the ADC units of the LPC 2148. The gates of the sixteen MOSFETs are signalled by a set of 16 bits output of one 32 bit port of the LPC 2148 through the 32 opto coupler devices.

The software has been designed with two major tasks. The first task is meant to convert the incoming DC voltage levels into corresponding digital quantities and these digital quantities are taken up by the ANN segment which returns the switching or step angles. The second but parallel task is to use the switching angles supplied by the ANN segment and generate the switching pulses with appropriate time conversion scheme such that the period of the ac output is 20 millisecond or 50 Hz

The ANN unit uses the same configuration as it was implemented in the MATLAB / SIMULINK model. The same activation functions viz sigmoidal in the input and hidden layers and a linear activation function in the output layer are implemented as C codes in the KEIL C environment. The same weights of synapses as decided or found by the MATLAB / SIMULINK training process is also used in the KEIL C code and the neural network thus realised in KEIL C mimics the one in MATLAB. The result of a sample case with V1 = V2 = V3 = V4 = 6V as input voltage combinations is presented in Figure 9. Interestingly the speed of operation of the ARM processor is very high as it is operated by a 100 MHz basic clock the calculations pertaining to one cycle of finding the switching instants for a given set of input voltages is much less than 8 milli seconds and as such it is possible to implement the newly calculated switching instants in the very next AC cycle period. The program is so timed that the monitoring of the incoming voltages and the estimation of the switching instants are carried out at the starting of every cycle of the required 50 Hz output.

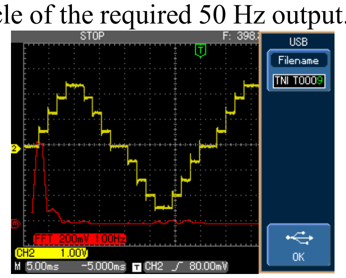

Figure.9 Output voltage and its FFT

VI CONCLUSION

The design of a novel practically realisable step modulated multilevel inverter with nine levels has been presented. The novel methodology for a practical real time usage exploiting the advantages of PSO and ANN has been demonstrated. The usefulness of the ARM processor LPC 2148 with its real time operating system feature has been demonstrated in the real time implementation of the SHE PWM with the software realised ANN module. The freedom from the usually specified condition $\theta1<\theta2<\theta3<\theta4$ in the case of a step modulated multilevel inverter has also been demonstrated. There are deep and vast areas of possible future research in the directions of MPPT under MLI environments when there are a number of renewable energy DC sources of fluctuating voltage nature.

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