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Analysis of 31-Level Asymmetrical Cascaded Multilevel Inverter Using GA & ANN

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ABSTRACT: Multilevel inverters(MLI) generate stepped output voltage waveform from DC voltage sources. For a Cascade H-bridge (CHB) Multilevel inverter, numerous H-bridges are linked in series and every H-bridge has a separate DC voltage source. In this paper, an Asymmetrical cascaded H-brigde MLI having four H-bridge is simulated making use of GA technique to evaluate the complex non-linear equations. Then the Neural Network is trained using data set obtained by GA to obtain optimum values of switching angles. The circuit is simulated for both GA & ANN technique using MATLAB/ Simulink software & the results obtained are presented.

KEYWORDS: Multilevel Inverters (MLI); Total Harmonic Distortion (THD); Cascaded H-Bridge (CHB); Selective Harmonic Elimination (SHE); Genetic Algorithm (GA); Artificial Neural Network (ANN).

I. INTRODUCTION

Multilevel Inverter (MLI) is broadly used in high & medium power applications. Different types of MLI are: Flying Capacitor Inverter (FC), Neutral Point Clamped Inverter (NPC) & Cascaded H-Bridge Inverter (CHB) [1]. Among these topologies, CHB inverter is chosen due to its straightforward configuration, easy expandability & capability to interface with renewable energy resources [2][3].Depending upon the magnitude of the DC voltage sources, CHB are classified as Symmetrical & Asymmetrical [4].

In a symmetrical CHB MLI the input voltage sources will have same magnitude. If 'N' is the number of H-bridges that are connected, it produces upto 'M' levels in the output voltage related by the equation given as: M=2N+1.
Thus, a symmetrical CHB MLI uses 15 H-bridges to produce 31-level stepped output voltage waveform.
In Asymmetrical CHB MLI the magnitudes of input DC voltage sources is in ratio. Here the ratio selected is V1:V2:V2:V3=1:2:4:8. is considered to generate 31-level [5]. Hence we can obtain the following relation for Asymmetrical CHB MLI : M=(2Nx2)-1
Where, M = number of levels in output voltage waveform & N = number of H-bridges in the circuit. An asymmetrical CHB MLI uses 4 H-bridges & only 16 switches to produce 31-level output waveform. Therefore asymmetrical configuration is preferred as it makes use of less number of components to produce higher level output voltage. Due to this reason, the switching losses reduce drastically.

Harmonics in the output voltage waveform can be reduced by making use of different PWM techniques such as Sinusoidal PWM , Space Vector PWM & Selective Harmonic Elimination PWM (SHE-PWM). Among these SHE-PWM technique is used to eliminate specific harmonics in the output. Different non-linear equations need to be solved in SHE techniques using intelligent methods.

Genetic Algorithm (GA)[6][7][8] technique is efficient and most commonly used procedure to eliminate specific order harmonics & to minimize THD. To further optimize the solution Artificial Neural Network (ANN) [9][10][11][12] technique is adopted to enhance the power quality of the output of the inverter. In this paper, a 31-level Asymmetrical CHB-MLI is considered & a comparative study on the performance of the same is made for different control techniques namely GA & ANN. The simulation results obtained from both these techniques are studied and conclusions are drawn.

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II. PRINCIPLE OF OPERATION OF PROPOSED CIRCUIT

In this paper, an Asymmetrical CHB MLI making use of 4 H-bridges is considered as shown in figure 1(a) to generate output voltage waveform having 31-level shown in figure 1(b). The magnitudes of input DC voltages are in ratio V1:V2:V2:V3=1:2:4:8 making use of 16 switches. Table 1 shows the switching sequence for producing 31-level output voltage.

The voltage rating of the voltage waveform in the output is preset as $V_{o\ rms}$ =230V.Therefore the peak voltage value is given as $V_m= \sqrt{2} * V_{o\ rms} = \sqrt{2} * 230=324V$.

Now to generate 31-level voltage output 15 steps are required in the positive half cycle. Each step will have voltage magnitude equal to $V_m/15=324/15= 21.6V$. But in asymmetrical configuration, the DC voltage sources are in the ratio of 1:2:4:8 to generate 31-levels. Thus the magnitudes of the DC voltages will be obtained as:

V1	V2	V3	V4	V_m=V1+V2+V3+V4
21.6V	43.2V	86.4V	172.8V	324V

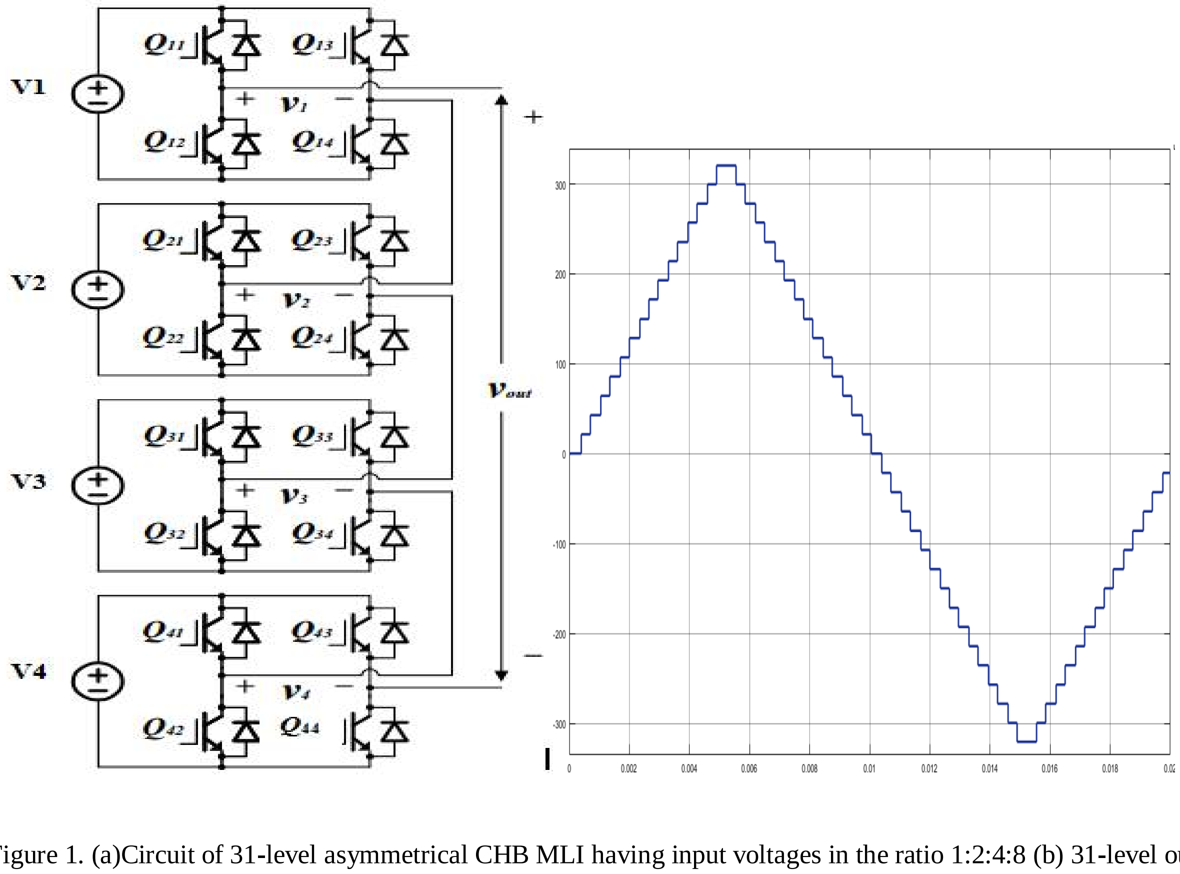

Figure 1. (a)Circuit of 31-level asymmetrical CHB MLI having input voltages in the ratio 1:2:4:8 (b) 31-level output voltage waveform generated by (a)

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Table 1. Switching sequence for Asymmetrical inverter to produce 31-levels having voltage sources in the ratio 1:2:4:8

V_{dc}	Q_{11}	Q_{12}	Q_{13}	Q_{14}	Q_{21}	Q_{22}	Q_{23}	Q_{24}	Q_{31}	Q_{32}	Q_{33}	Q_{34}	Q_{41}	Q_{42}	Q_{43}	Q_{44}
15	1	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1
14	1	0	0	0	1	0	0	1	1	0	0	1	1	0	0	1
13	1	0	0	1	1	0	0	0	1	0	0	1	1	0	0	1
12	1	0	0	0	1	0	0	0	1	0	0	1	1	0	0	1
11	1	0	0	1	1	0	0	1	1	0	0	0	1	0	0	1
10	1	0	0	0	1	0	0	1	1	0	0	0	1	0	0	1
9	1	0	0	1	1	0	0	0	1	0	0	0	1	0	0	1
8	1	0	0	0	1	0	0	0	1	0	0	0	1	0	0	1
7	1	0	0	1	1	0	0	1	1	0	0	1	1	0	0	0
6	1	0	0	0	1	0	0	1	1	0	0	1	1	0	0	0
5	1	0	0	1	1	0	0	0	1	0	0	1	1	0	0	0
4	1	0	0	0	1	0	0	0	1	0	0	1	1	0	0	0
3	1	0	0	1	1	0	0	1	1	0	0	0	1	0	0	0
2	1	0	0	0	1	0	0	1	1	0	0	0	1	0	0	0
1	1	0	0	1	1	0	0	0	1	0	0	0	1	0	0	0
0	1	0	0	0	1	0	0	0	1	0	0	0	1	0	0	0
-1	0	1	1	0	0	1	0	0	0	1	0	0	0	0	1	0
-2	0	1	0	0	0	1	1	0	0	1	0	0	0	0	1	0
-3	0	1	1	0	0	1	1	0	0	1	0	0	0	0	1	0
-4	0	1	0	0	0	1	0	0	0	1	1	0	0	0	1	0
-5	0	1	1	0	0	1	0	0	0	1	1	0	0	0	1	0
-6	0	1	0	0	0	1	1	0	0	1	1	0	0	0	1	0
-7	0	1	1	0	0	1	1	0	0	1	1	0	0	0	1	0
-8	0	1	0	0	0	1	0	0	0	1	0	0	0	1	1	0
-9	0	1	1	0	0	1	0	0	0	1	0	0	0	1	1	0
-10	0	1	0	0	0	1	1	0	0	1	0	0	0	1	1	0
-11	0	1	1	0	0	1	1	0	0	1	0	0	0	1	1	0
-12	0	1	0	0	0	1	0	0	0	1	1	0	0	1	1	0
-13	0	1	1	0	0	1	0	0	0	1	1	0	0	1	1	0
-14	0	1	0	0	0	1	1	0	0	1	1	0	0	1	1	0
-15	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1	0

III. CONTROL TECHNIQUES FOR MULTILEVEL INVETER

THD can be minimized using different modulation techniques. The most popular Pulse Width Modulation (PWM) techniques are Sinusoidal PWM, Space Vector PWM & Selective Harmonic Elimination PWM technique. The SHE-PWM technique is widely used to reduce specific lower order harmonics in the output voltage. Finding solution to different non-linear equations in SHE technique is quite complex. Therefore intelligent methods such as Particle Swarm Optimization technique(PSO), Genetic Algorithm technique(GA), Ant Colony Optimization technique(ACO)etc are adopted. Among these Genetic Algorithm technique is efficient and most commonly used procedure to eliminate specific order harmonics & to minimize THD

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A. Genetic Algorithm (GA):

GA uses concepts of biological evolution in optimizing the solution. This method does not include mathematical modelling & no initial guess is required , thus making this technique simple & efficient.

The procedure to apply Genetic Algorithm for optimization is as follows:

1) Initializing the population: The population size nothing but number of general solutions(chromosomes) which needs to be initialized. Each switching angle is referred as a Gene. In our program, the population size is set as 20 and the switching angles $\theta_1,\theta_2, \theta_3,\ldots\ldots \theta_{15}$ represent 15 genes for producing 31-level output. The initial population is chosen arbitrarily to the condition that the angles must be in the ascending order lying between 0° to 90°.
2) Evaluating the fitness function: For our application, the objective function is THD, which is minimized to get better quality output.
3) Selection: By the selection rules, the parents are selected in order to generate offspring for reproducing nextgeneration. The fittest individuals survive and the rest perish.
4) Crossover & Mutation: During crossover, the genes are interchanged to give superior offspring. Mutation is where changes take place within the same gene. These operators broaden the search space & avoid algorithm to attain local minimum.
5) Stop Criteria: Is the condition that terminates the algorithm. The algorithm is set to 250 iteration as the stop criterion.

Selective Harmonic Elimination(SHE) method eliminates certain selected order harmonics to decrease overall harmonic content in the output waveform. Due to this the %THD is minimized. In this method, the selected order harmonic is eliminated by solving complex non-linear equations as shown below:

For multilevel inverters, the Fourier series expansion of the stepped voltage waveform is given as,

$$V(t) = \sum_{n=1}^{\infty}(a_n \sin(n\alpha_n) + b_n \cos(n\alpha_n)) \ldots. (1)$$

The even harmonics are nullified (b_n=0) and only odd harmonics are considered because of quarter symmetry of the waveform. The value of a_n is computed from Fourier series factor.
α_1, α_2, …, α_m, are the switching angles from only the first quadrant switching angles considered for calculations due to symmetry of the waveform given as:

$$a_n= (4V_{dc}/n\pi) \sum_{k=1}^{m} \cos(n\alpha_k) \ldots\ldots\ldots\ldots\ldots\ldots (2)$$
$$0<\alpha_1< \alpha_2<\alpha_3<\ldots\ldots\ldots\alpha_m <\frac{\pi}{2} \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Equation(2) is expressed till kth term for any harmonics, where ‘m’ is the number of switching angles in the first quadrant represented as α_1 to α_m satisfying equation (3). ‘M’ is the desired value for fundamental component represented in equation (4) & other harmonics are equated to zero to eliminate it as shown in equation (5) & (6)

$$a_1= (4V_{dc}/\pi) \sum_{k=1}^{m} \cos(\alpha_k) = M\ldots\ldots (4)$$
$$a_5= (4V_{dc}/5\pi) \sum_{k=1}^{m} \cos(5\alpha_k) = 0\ldots\ldots(5)$$
$$a_n= (4V_{dc}/n\pi) \sum_{k=1}^{m} \cos(n\alpha_k) = 0 \ldots\ldots(6)$$

The complex non-linear equations to eliminate selected harmonic content is evaluated using GA technique to give optimum switching angles. Thus minimizing the THD value. The switching angles got from the GA MATLAB code are as shown in table 2:

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Table 2. Switching angles obtained from GA MATLAB code to genearate 31-levels

Switching Angles		Switching Angles		Switching Angles	
θ_1	2.96°	θ_6	22.23°	θ_{11}	47.60°
θ_2	7.26°	θ_7	27.58°	θ_{12}	55.64°
θ_3	14.87°	θ_8	39.38°	θ_{13}	61.27°
θ_4	16.99°	θ_9	45.57°	θ_{14}	61.79°
θ_5	19.27°	θ_{10}	47.21°	θ_{15}	84.78°

The disadvantage of GA is that it does not give the exact solution but gives the best solution. Also, being stochastic there is no guarantee on the optimality or the quality of the solution. GA only focuses on the fitness value rather than understanding it. As a result it is difficult to justify the quality of the obtained solution. Therefore we can adopt other techniques to improve quality of the output voltage. In genetic algorithm technique, a large look-up table is required to estimate real-time switching angles. This look-up table can be substituted by a well trained neural network which has the capability of obtaining generalized solutions so that the solution gap is filled properly.

B. Artificial Neural Network (ANN)

An artificial neural network is a mathematical model that replicates the structure & functions of the biological neural network. It is an interconnected network of artificial neurons and evaluates information for computation purpose. Mostly, ANN adapts its structure according to the information given to it during the training process. They can be used to model non linear relationships between inputs and outputs or to find patterns in them.

The procedure to apply ANN for optimization is as follows:

1) Various set of input voltages and switching angles are obtained after solving the harmonic elimination equations using GA or any other technique.
2) The obtained data sets are tabulated for 100 samples and used for training the neural network with select percentage 65% for training (used to adjust weight so that the error obtained is least.);
   20% for validation(used to measure the generalization of the network);
   15% for testing(used to evaluate the performance during & after training.)
3) There are different training methods & neural network models. Here Back-propagation is training method selected for a multi-layer feed forward network with 2 layers (Hidden & output layer). It has 24 neurons in the hidden layer & 15 neurons in the output layer (15 switching angles).
4) The training is normally done offline because it is time-consuming. A number of back-propagation training methods are present, but the Levenberg–Marquardt (L-M) algorithm is used because of its fast convergence
5) The training must be continued till MSE(Mean Square Error) is nearly 0 & R(Regression) is nearly 1. Figure 2 shows values of (a)MSE=1.37×10^{-2}& (b)R=0.96 obtained after training the ANN in MATLAB.
6) The switching angles are displayed by the trained networkas shown in table3 & then given to the inverter to reduce the THD values less than 5% and reduce the overall harmonic contents in the output.

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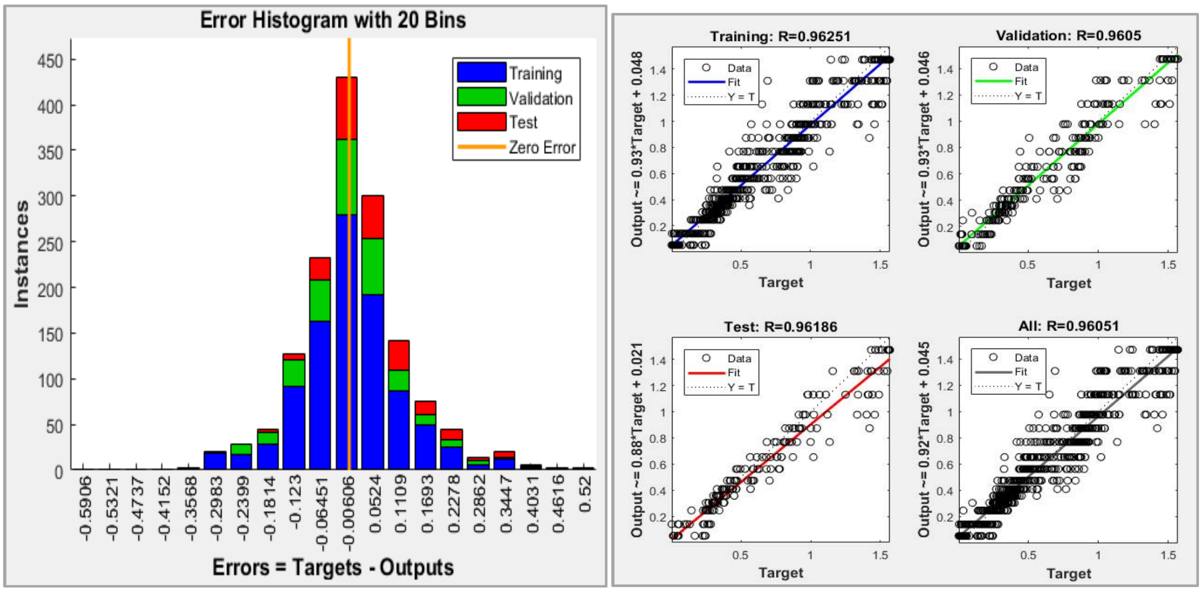

Figure 2. (a) Error Histogram & (b) Regression graphs for the Trained Neural Network

IV. DESIGN OF FILTER

Capacitor filter is designed to minimize the ripple content in the output of the inverter. This resonant parallel circuit contains an inductor and a resistor in parallel with a capacitive load. Condition for parallel resonant circuit is given as:

$$I_C = I_L \sin \phi$$

$$\frac{\omega L}{R^2 + (\omega L)^2} = \omega C$$

$$C = \frac{L}{R^2 + (\omega L)^2}$$

Where $\omega = 2\Pi f$ in rad; L is Load inductor; R is resistor; C is capacitor

For instance, for R=25Ω & L=20mH, C=30μF. Similarly we can obtain the Capacitance values for various RL loads as in table 4.

Table 4. Values of Capacitors for various RL loads

R in Ω	L in mH	C in μF
25	20	30
25	50	57
25	100	62

V. SIMULATION RESULTS AND DISCUSSION

The MATLAB/SIMULINK circuit for Asymmetrical CHB inverter to generate 31-levels in the output voltage waveform is as shown in Figure 3. It consists of four H-Bridges and sixteen MOSFETS's. The four DC input voltages sources of value V1=21.6V, V2=43.2V, V3=86.4V, V4=172.6V are given to the inverter.

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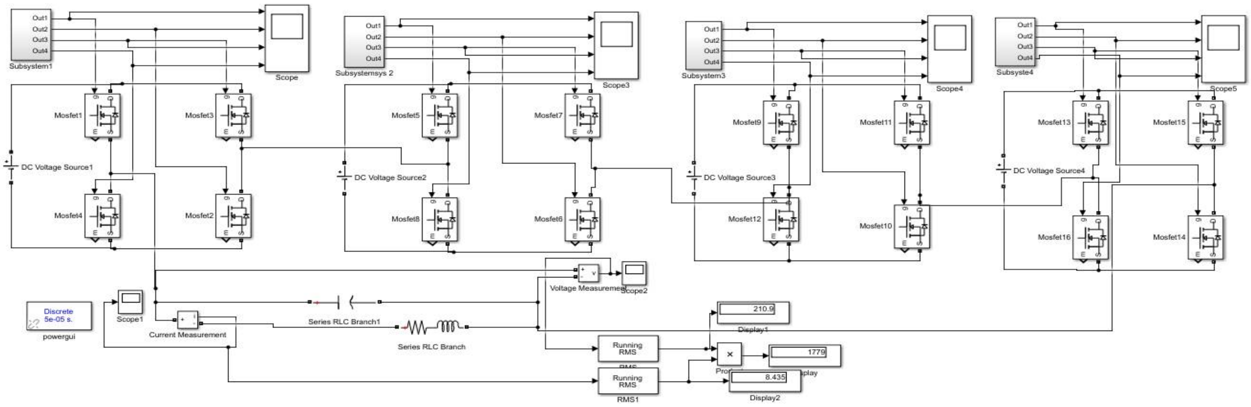

Figure 3. MATLAB Simulink circuit for Asymmetrical CHB inverter to produce 31-levels

Figure 4&figure 5 gives the output voltage waveform and its FFT analysis for R=25Ω, L=100mH using GA & ANN technique respectively. Table 5&6 shows the simulated results obtained by FFT analysis of output voltage waveform for load R=25Ω & inductance varying from 20mH to 100mH using GA & ANN respectively.

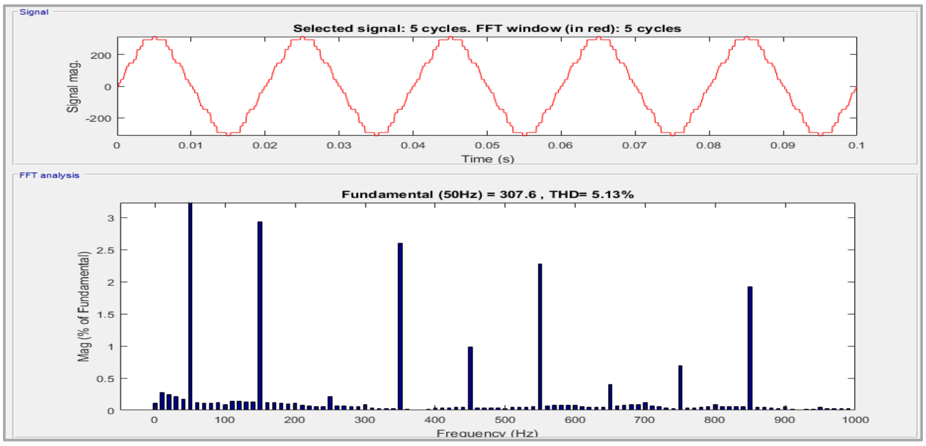

Figure 4.Output voltage waveform and FFT analysis with R=25 Ω, L=100mH using GA

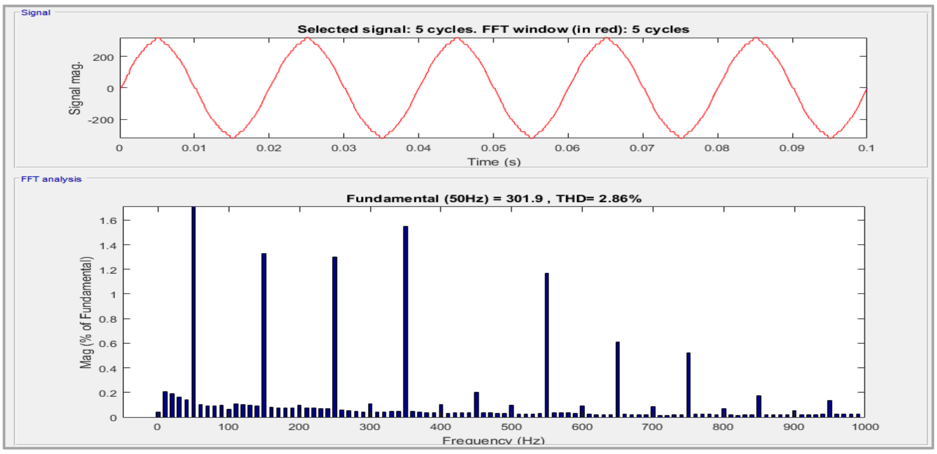

Figure 5. Output voltage waveform & FFT analyis for R=25Ω & L=100mH using ANN

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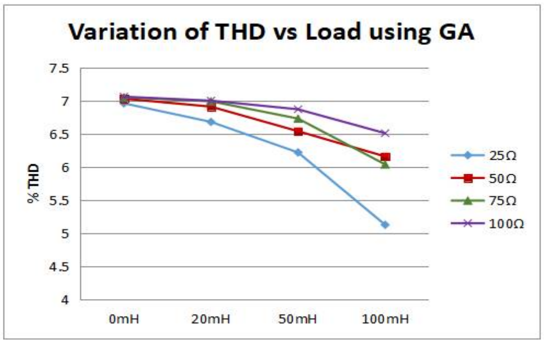
Table 5. Results obtained for 31-level CHB-MLI using GA technique

R in Ω	L in mH	C in μF	V rms Volts	I rms Amps	P rms Watt	THD in %	Harmonics 3rd	5th	7th	9th
25	0	0	210.8	8.43	1779	6.96	4.76	0.13	2.31	2.13
25	20	30	211.8	8.19	1737	6.68	4.38	0.07	2.70	1.73
25	50	57	214.0	7.24	1551	6.22	3.93	0.22	2.90	1.24
25	100	62	217.7	5.47	1192	5.13	2.94	0.22	2.60	0.99

Table 6. Results obtained for 31-level CHB-MLI using ANN technique

R in Ω	L in mH	C in μF	Vrms volts	I rms amps	P in Watt	THD in %	Harmonics 3rd	5th	7th	9th
25	0	0	208.4	8.334	1736	3.63	2.31	0.32	2.18	0.61
25	20	30	209	8.1	1693	3.22	1.96	0.71	1.89	0.38
25	50	57	210.8	7.149	1507	3.03	1.68	1.02	1.68	0.29
25	100	62	213.6	5.373	1148	2.86	1.33	1.30	1.55	0.20



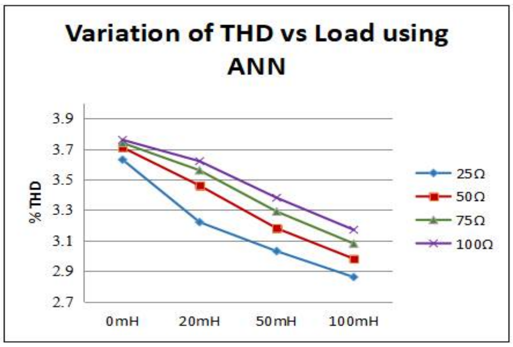


Figure 6.Variation of THD Vs RLC-Load using GA& ANN respectively

Figure 6 shows graph of variation of THD for various load conditions using GA & ANN technique respectively. It is found that the %THD is lowest for load R=25 Ω & L=100mH which is 5.13% using GA & 2.86% using ANN. Thus ANN minimizes the THD drastically within standards & improves the power quality of the output. From the figures it is also seen that the %THD reduces, with decrease in resistance and with increase in the inductance varying from 20mH to 100mH.

VI. CONCLUSION

Asymmetrical Cascaded H-Bridge Multilevel inverter using four H-Bridges & 16 switches is proposed to get 31-level voltage waveform in this paper. The PWM technique used to obtain desired output is Selective Harmonic Elimination PWM technique to eliminate certain lower order harmonics and thereby improve the quality of output & minimize the THD. To resolve the complex non-linear equations obtained by SHE method for higher level outputs, GA technique is used so that the solution obtained is efficient & fast. To further optimize the switching angle values, the data obtained from GA is fed into Artificial Neural Network to train it. From the results it is observed that ANN techniques gives reduced THD values of 2.86% for load R=25 Ω & L=100mH.

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