Comparative Analysis of 13-level Asymmetrical Multi-level Inverter Using Different Control Techniques

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Abstract – *This paper presents an Asymmetrical Multi-level Inverter which generates stepped AC output voltage with the input DC voltage sources. The number of input DC sources used are less and are of lower magnitudes. The proposed Multi-level Inverter in Asymmetrical configuration has unequal DC sources produce 13-levels of output. The control techniques Equal Phase (EP) method, Half Equal Phase (HEP) method, Feed Forward (FF) method and Half Height (HH) method are used for the calculation of switching angles for the Multi-level Inverter. The inverter is simulated using all the four control techniques using MATLAB/ Simulink software. The performance of the inverter is analyzed and the comparison on Total Harmonic Distortion is presented.*

***Keywords*:** Multi-level Inverter (MLI), Asymmetrical Multi-level Inverter (AMLI), Equal Phase (EP) method, Half Equal Phase (HEP) method, Feed Forward (FF), Half Height (HH), Total Harmonic Distortion (THD).

1.INTRODUCTION *(Size 11 , cambria font)*

Inverters are one among the types of converters used to convert input DC to AC output. Multi-level inverters are important tool of power converters used elaborately in high and medium power applications. Due to stepped output waveform, multi-level inverters produce lower harmonics and has better power quality of output voltage compared to two level and three level inverters.

A review on MLI topologies with reduced device count has been presented [1] which gives the understanding of the challenges that is been encountered in the newer topologies during the reduction of number of devices. Multi-level Inverter topologies like diode-clamped inverter (neutral-point clamped), flying capacitor (capacitor clamped) inverter and Cascaded H-Bridge inverters have been reviewed and also relevant control techniques [2].

The three classical topologies of MLI are Neutral Point Clamped (NPC) [3], Flying Capacitor [4], Cascaded H-Bridge [5]. But NPC and FC topologies suffer from DC-link voltage balancing problem, bulk size of capacitor and requires a greater number of semiconductor components at higher levels [6]. The Asymmetrical Inverters overcome the drawback of using same value of DC sources [7]. An arrangement of semiconductor switches with mixed DC sources to obtain maximum voltage levels to improve the power quality [8].

The staircase output waveform of the MLI is obtained by fundamental frequency PWM schemes by calculating switching angles for each step and thereby minimizing THD of the MLI [9]. Switching angle calculation and percentage conduction of each switch are calculated using Equal Phase (EP) method, Half Equal Phase (HEP)method, Feed Forward (FF) method and Half Height (HH) method by non-linear equations. The optimum switching angles are calculated by each method [11] to validate the results.

In this paper, a 13-level Asymmetrical MLI is considered a comparative study on the performance using different control techniques is presented. The simulation results obtained are studied and conclusion are drawn.

1.1 PRINCIPLE OF OPERATION OF PROPOSED CIRCUIT

This topology uses eight voltage sources in which the voltage sources in each module are in the ratio 1:2. By having unequal DC sources, the MLI produces different output voltage levels by fewer semiconductors and lower harmonic components as well.

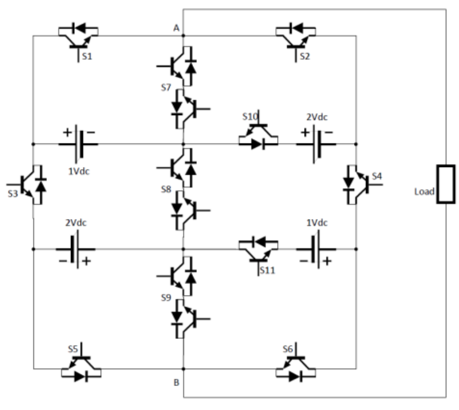


Fig 1. Proposed Topology

Fig 1 represents the proposed topology with 14 switches (8 unidirectional switches and 3 bidirectional switches), 14 diodes and 4 unequal DC sources. This configuration generates 6 positive levels, 6 negative levels and zero level (totally 13 levels). The module can be connected Fig 1 Proposed MLI Topology in series as cascade connection easily to obtain higher levels. The switching pulses are selected in such a way that there is less stress on switches. Table1 shows the switching pattern of the inverter.

TABLE 1 Switching Table of 13-level Inverter

	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}
0v	0	0	0	0	0	0	1	1	1	0	0
1v	1	0	0	0	0	0	0	1	1	0	0
2v	0	0	0	0	1	0	1	1	0	0	0
3v	1	0	0	0	1	0	0	1	0	0	0
4v	1	0	0	1	0	0	0	0	1	1	1
5v	0	0	0	1	1	0	1	0	0	1	1
6v	1	0	0	1	1	0	0	0	0	1	1
-1v	0	0	1	0	1	0	1	0	0	0	0
-2v	1	0	1	0	0	0	0	0	1	0	0
-3v	0	0	1	0	0	0	1	0	1	0	0
-4v	0	0	1	0	0	1	1	0	0	0	1
-5v	0	1	1	0	0	0	0	0	1	1	0
-6v	0	1	1	0	0	1	0	0	0	1	1

2. CONTROL TECHNIQUES FOR MULTILEVEL INVERTER

Switching angle is the moment of the voltage level change at the output. For an
m-level waveform there are 2(m-1) switching angles are needed. We call them as $\alpha 1, \alpha 2, \alpha 3 \ldots\ldots \alpha m\text{-}2, \alpha m\text{-}1$. Since the sine wave is a symmetrical waveform, the negative half cycle is centrally symmetrical to its positive half cycle; and the waveform of the second quarter period is mirror symmetrical to the waveform of its first quarter period. So, we call the switching angles in the first quadrant period i.e., 0º-90 º as main switching angles. Main Switching Angles in the first quarter of the sine wave (i.e., 0º to 90º):

$\alpha 1, \alpha 2, \alpha 3 \ldots\ldots, \alpha(m-1)/2$ .... (1)

The switching angles in the second quarter of the sine wave (i.e., 90º to 180º) are:

$\alpha(m+1)/2=\Pi-\alpha(m-1)/2, \Pi-\alpha(m-2)/2 \ldots\ldots \Pi-\alpha 1$ ....(2)

The switching angles in third quadrant of the sine wave (i.e.,180º to 270º) are $\alpha m=\Pi+\alpha 1 \ldots\ldots, \Pi+\alpha(m-1)/2$ .... (3)

The switching angles in the fourth quadrant (i.e.,270º to 360º) are

$\alpha(3m-1)/2=2\Pi-\alpha(m-1)/2 \ldots\ldots\ldots 2\Pi-\alpha 1$ .... (4)

From the above analysis it was concluded that we need to determine only the main switching angles (i.e., from 0º to 90º), the other switching angles (i.e., from 90º to 360º) can be obtained from the main switching angles in the first quadrant.

The main switching angles of the proposed inverter are determined from the following methods.

2.1Equal Phase (EP) Method:

In the equal phase method, the switching angles are distributed averagely in the range 0-π.The main switching angles are obtained by the formula given below:

$$\alpha i = \frac{180*i}{N}$$ where i=1, 2....... (m-1)/2 .... (5)

The main switching angles, by EP method, of the proposed 13-level inverter are determined from the equation (5) α1=13.84º, α2=27.69º, α3=41.53º, α4=55.38º, α5=69.23º

The other switching angles in second, third and fourth quadrants of sine wave are derived from the main switching angles according to the equations (2), (3) and (4). Table 2 shows the total switching angles required to get the sinusoidal wave shape by EP method.

Table 2 Switching Angles of Equal Phase Method

	Switching Angles		Switching Angles
α1	13.84	α14	193.84
α2	27.69	α15	207.69
α3	41.53	α16	221.53
α4	55.38	α17	235.38
α5	69.23	α18	249.23
α6	83.07	α19	263.07
α7	96.92	α20	276.92
α8	110.76	α21	290.76
α9	124.61	α22	304.61
α10	138.46	α23	318.46
α11	152.30	α24	332.30
α12	166.15	α25	346.15
α13	180	α26	360

2.2 Half Equal Phase (HEP) Method:

The waveform obtained from the EP method looks like a triangle waveform, so to get some better output waveform, another method called Half Equal Phase Method (HEPM) is established, by this approach we can get better and reduced harmonic output waveform. The main switching angles are in the range 0º-90º, which are obtained by the formula given below. $\alpha i = \frac{180*i}{N+1}$ where i=1,2......... (m-1)/2 ....(6)

For the proposed 13-level inverter the main switching angles, by HEP method, are calculated from the equation (6). α1=12.85º, α2=25.71º, α3=38.57º, α4=51.42º, α5=64.28º After that the other switching angles are derived from the above main switching angles, according to the equations (2), (3) and (4). And are tabulated in Table 3.

Table 3 Switching Angles of Half Equal Phase Method

	Switching Angles		Switching Angles
α_1	12.85	α_{14}	192.85
α_2	25.71	α_{15}	205.71
α_3	38.57	α_{16}	218.57
α_4	51.42	α_{17}	231.42
α_5	64.28	α_{18}	244.28
α_6	77.14	α_{19}	257.14
α_7	102.85	α_{20}	282.85
α_8	115.71	α_{21}	295.71
α_9	128.57	α_{22}	308.57
α_{10}	141.42	α_{23}	321.42
α_{11}	154.28	α_{24}	334.28
α_{12}	167.14	α_{25}	347.14
α_{13}	180	α_{26}	360

2.3 Feed Forward (FF) Method:

In the above three methods, we can observe that there are wider gaps between the positive half-cycle and negative half-cycle. In order to reduce the gaps in between the positive half cycle and negative half-cycle, another approach called the Feed Forward Method (FFM) was established to find the main switching angles. The main switching angles are determined by the following formula.

$$\alpha i = \frac{1}{2}\sin^{-1}\frac{2i-1}{N-1}$$

where i=1,2............. (m-1)/2........................... (7)

The main switching angles, by FF method, of the proposed 13-level inverter are α1=2.39º, α2=7.23º, α3=12.31º, α4=17.84º, α5=24.29º After that **the** other switching angles are derived from the main switching angles, by using equations (2), (3) and (4). Table4 shows the total switching angles, of the proposed inverter, by FF method.

Table 4 Switching Angles of Feed Forward Method

	Switching Angles		Switching Angles
α_1	2.39	α_{14}	182.39
α_2	7.23	α_{15}	187.23
α_3	12.31	α_{16}	192.31
α_4	17.84	α_{17}	197.84
α_5	24.29	α_{18}	204.29
α_6	33.22	α_{19}	213.22
α_7	146.77	α_{20}	326.77
α_8	155.70	α_{21}	335.70
α_9	162.15	α_{22}	342.15
α_{10}	167.68	α_{23}	347.68
α_{11}	172.76	α_{24}	352.76
α_{12}	177.60	α_{25}	357.60
α_{13}	182.39	α_{26}	362.39

2.4 Half Height (HH) Method:

In the above two methods the switching angles are arranged in a simple manner, but the waveform at the output is not a sine wave shape. According to the sine function a new method called Half Height Method (HEM) was established to determine new switching angles. The main switching angles are obtained from the following formula.

$$\alpha i = \sin^{-1}\frac{2i-1}{N-1}$$

where i=1, 2............. (m-1)/2........................... (8)

In this method the main switching angles of the proposed 13-level inverter are α1=4.78º, α2=14.47º α3=24.62º, α4=35.68º, α5=48. 59º.The other switching angles are derived from the main switching angles according to the equations (2), (3) and (4). Table5 shows the total switching angles, by HH method, needed to get the sinusoidal wave shape.

Table 5 Switching Angles of Half Height Method

	Switching Angles		Switching Angles
α_1	4.78	α_{14}	184.78
α_2	14.47	α_{15}	194.47
α_3	24.62	α_{16}	204.62
α_4	35.68	α_{17}	215.68
α_5	48.59	α_{18}	228.59
α_6	66.44	α_{19}	246.44
α_7	113.55	α_{20}	293.55
α_8	131.40	α_{21}	311.40
α_9	144.31	α_{22}	324.31
α_{10}	155.37	α_{23}	335.37
α_{11}	165.52	α_{24}	345.52
α_{12}	175.21	α_{25}	355.21
α_{13}	184.78	α_{26}	364.78

4 SIMULATION OF PROPOSED CIRCUIT & DICUSSION OF RESULTS

Fig 2 shows the Simulink model of 13-level multi-level inverter. Fig 3 shows the switching pulses given to the inverter. To check the performance of proposed 13-level Asymmetrical MLI to generate 13 output voltage levels. The circuit is simulated through MATLAB Simulink software. The magnitude of DC sources used in the simulation circuit are 1VDC and 2VDC to which the inverter generates the output voltage of 13 levels. The switches used are IGBT which operates at fundamental switching frequency of 50Hz. Table 6 depicts the specifications considered for the simulation of the inverter.

TABLE 6 Specifications of 13-level Inverter

V1 = V3 = 60V V2 = V4 = 120V
R load; R= 25.45 Ω
RL load; R= 20.36 Ω, L= 48.6mH

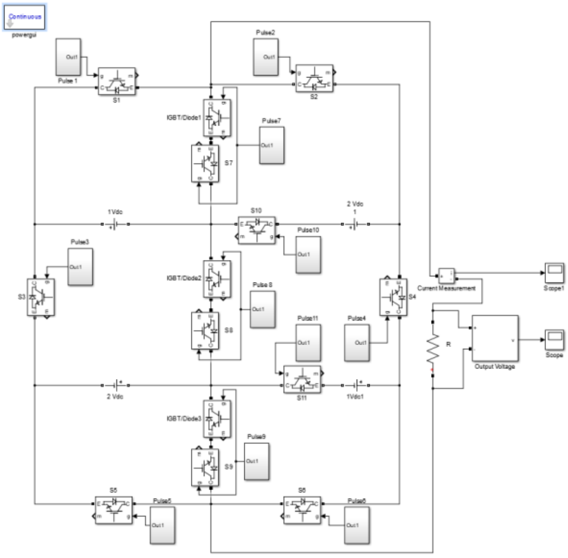


Fig 2 Simulation model of proposed topology

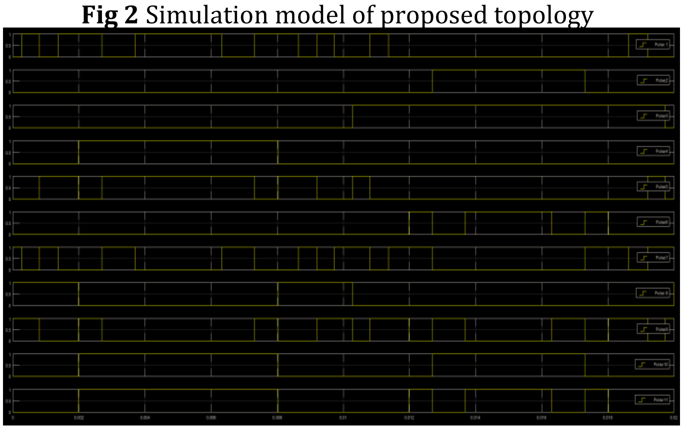
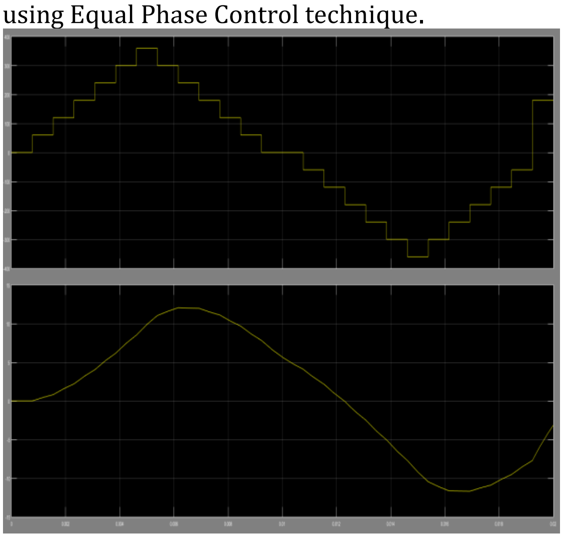


Fig3 Switching pulses

Fig 4 shows the output voltage and current waveform for R and RL load using Equal Phase Control technique. Fig 5 shows the FFT analysis of the 13-level inverter for R and RL load using Equal Phase Control technique.



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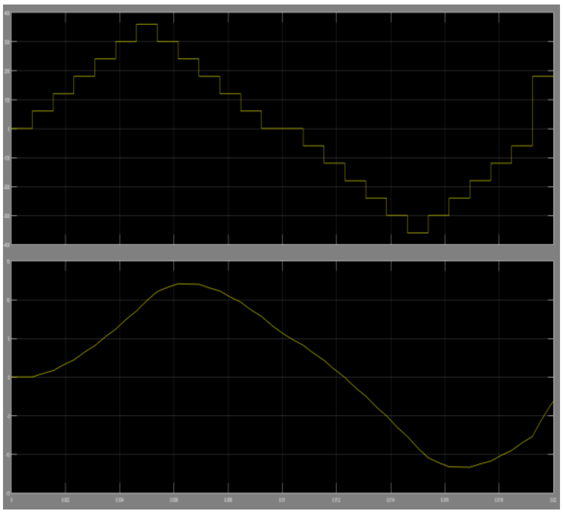
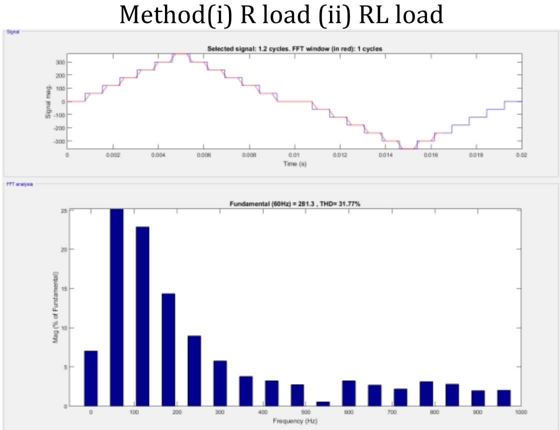


(ii)

Fig 4 Output voltage and current waveform of Equal Phase Method(i) R load (ii) RL load



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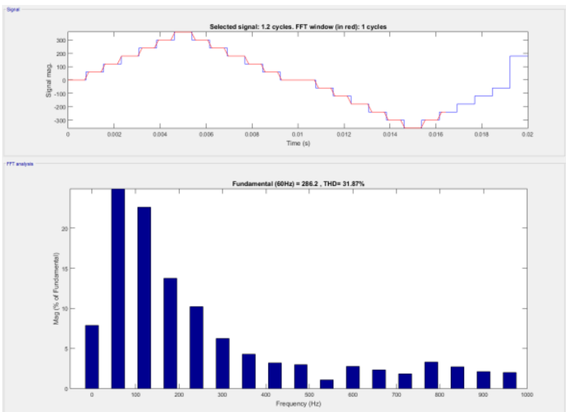

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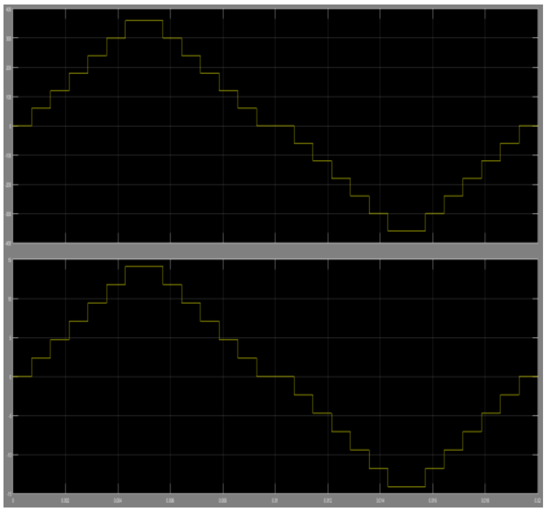
Fig 5 FFT analysis of Equal Phase Method (i) R load (ii) RL load

Fig 6 shows the output voltage and current waveform for R and RL load using Half Equal Phase Control technique. Fig 7 shows the FFT analysis of the 13-level inverter for R and RL load using Half Equal Phase Control technique.



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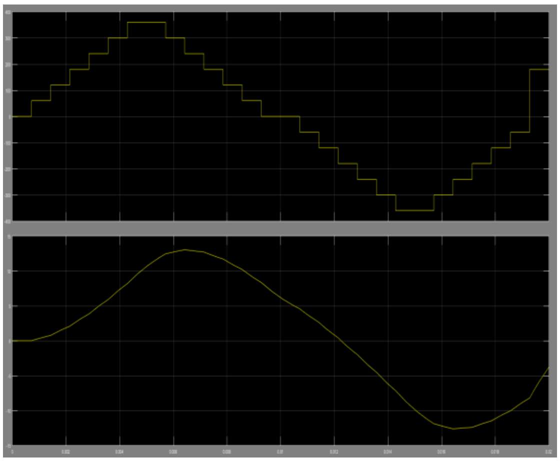

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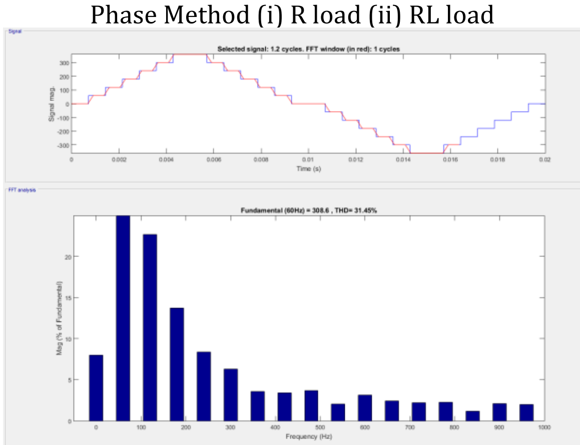
Fig 6 Output voltage and current waveform of Half Equal Phase Method (i) R load (ii) RL load



(i)

Fig 8 shows the output voltage and current waveform for R and RL load using Feed Forward Control technique. Fig 9 shows the FFT analysis of the 13-level inverter for R and RL load using Feed Forward Control Technique.

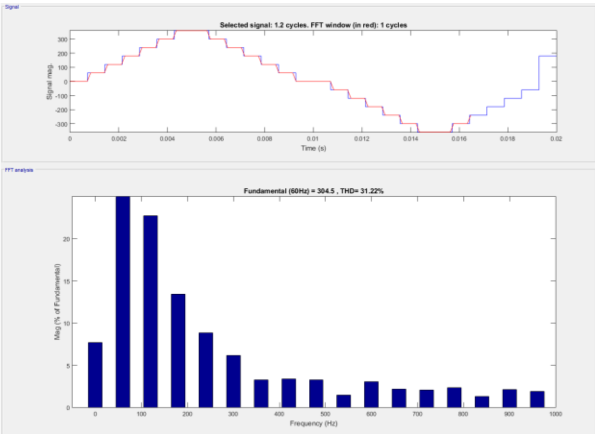


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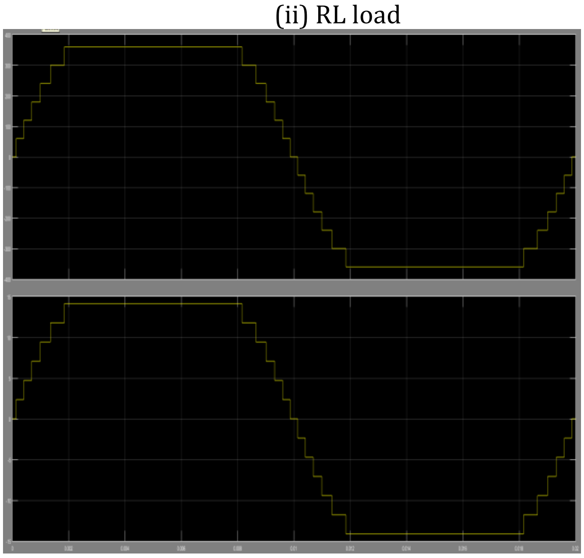
Fig 7 FFT analysis of Half Equal Phase Method (i) R load (ii) RL load



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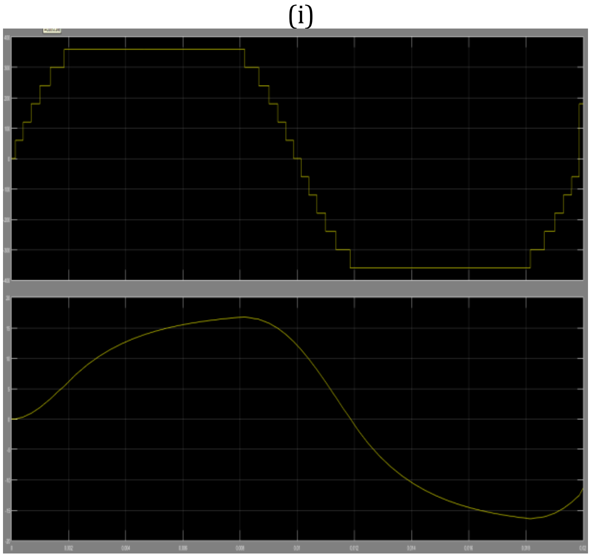

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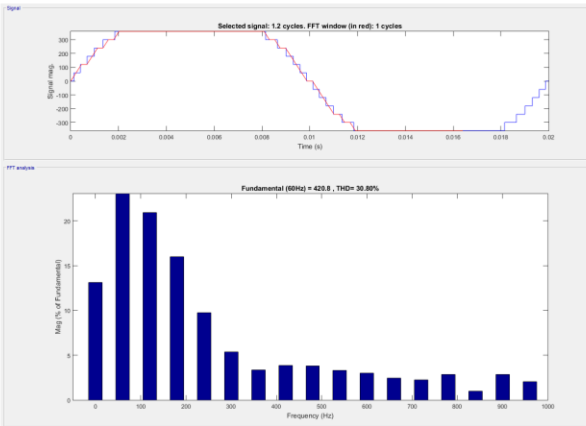
Fig 8 Output voltage and current waveform of Feed Forward Method (i) R load (ii) RL load



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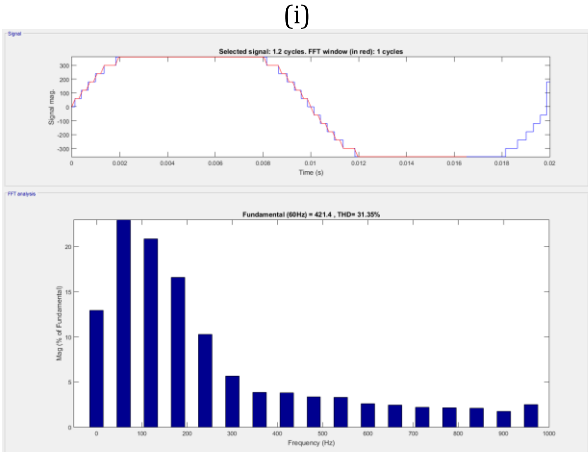

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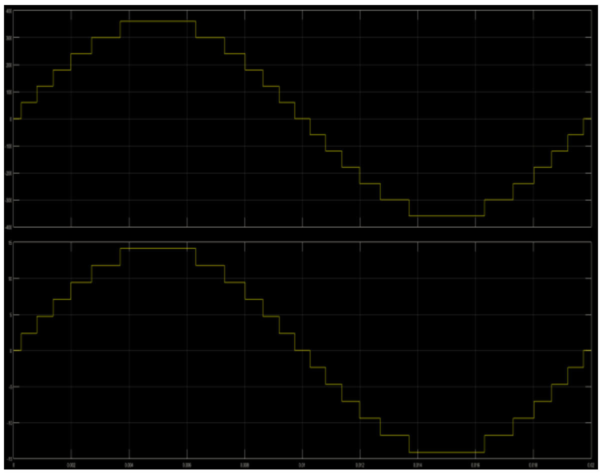
Fig 9 FFT analysis of Feed Forward Method (i) R load (ii) RL load

Fig 10 shows the output voltage and current waveform for R and RL load using Half Height Control technique. Fig 11 shows the FFT analysis of the 13-level inverter for R and RL load using Half Height Control Technique. Table 6 shows the comparison between control techniques with respect to Total Harmonic Distortion.



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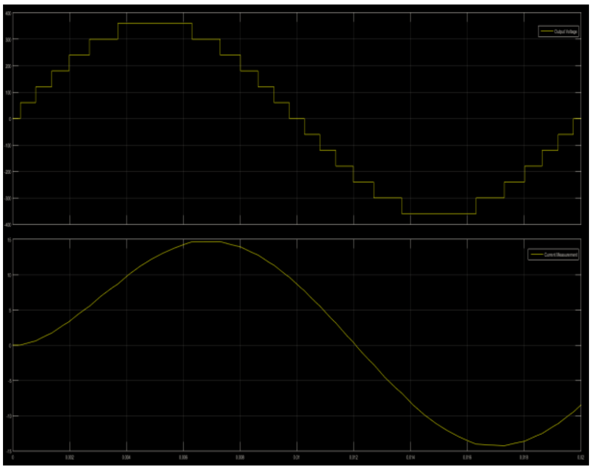
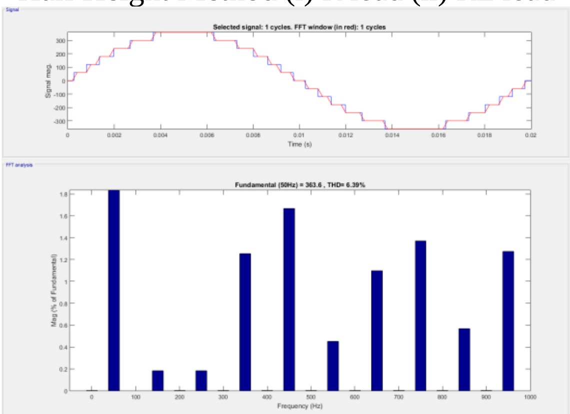


(ii)

Fig 10 Output voltage and current waveform of Half Height Method (i) R load (ii) RL load



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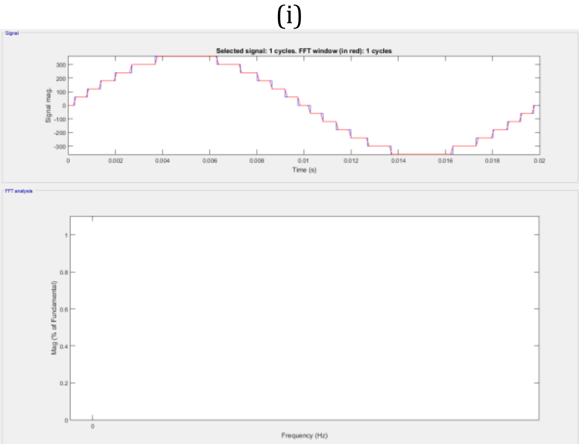

(ii)

Fig 11 FFT analysis of Half Height Method (i) R load (ii) RL load

Table 6 Comparison of control techniques

	THD in %	
Control Technique/ Load	R load	RL load
Equal Phase Method	31.77%	31.87%
Half Equal Phase Method	31.45%	30.02%
Feed Forward Method	30.8%	31.42%
Half Height Method	6.39%	6.93%

3. CONCLUSION

In this paper a comparative study on performance of 13-level Asymmetrical MLI using different control techniques is carried out. The simulation for all the techniques is done using MATLAB/ Simulink and the results obtained are presented. The simulation results show that the THD obtained for load R=20.36Ω & L=48.6mH is 31.77% for Equal Phase Angle technique, whereas for Half Height is 6.37%. Further studies can be conducted by incorporating soft computing techniques for better results.

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