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Design of a 25-level Asymmetrical Multi-Level Inverter with Reduced THD

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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. This paper presents An Asymmetrical Multi-Level Inverter with cascaded connection to generate 25 levels output. In this paper, the switching angles are calculated by Equal Phase (EP) method, Half Equal Phase (HEP) method, Feed Forward (FF) method and Half Height (HH) method. A comparison is carried out with different control techniques which can give reduced Total Harmonic Distortion. The simulation works are carried out through MATLAB/ Simulink software to demonstrate the performance of presented 25-level Asymmetrical Multi-level Inverter. The output voltage of the proposed topology satisfies the harmonics standard (IEEE 519) without any filter at the output side.

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).

I.INTRODUCTION

An inverter also called as power inverter is a power electronics device which converts Direct Current (DC) to Alternating Current (AC). Using few switches and control circuits AC output can be got at any required voltage and frequency. The few most commonly used inverters are square wave inverters, pure sine wave inverters, modified sine wave inverters and multi-level inverters. A MLI is a power electronic device which provides alternating voltage level at the output side using lower DC voltage levels as input. To get smoother waveform at the output number of levels need to be increased. Smoothness of the waveform is proportional to the voltage levels, as number of voltage levels increases the output waveform becomes smoother but the controller complexity and number of components will increase.

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.

The proposed topology has two modules, each module having 14 switches and 4 DC sources. The two modules are cascaded to get 25 levels of output. The switching angles are calculated by EP, HEP and HH methods. This paper is divided into sections. Section II is the proposed topology which consists of module configuration, equivalent circuits and description. Section III is switching angle calculation. Section IV is simulation results and performance. Section V is conclusion and future scope.

II.PRINCIPLE OF OPERATION OF PROPOSED CIRCUIT

This topology uses 8 voltage sources in which 4 are 1Vdc and the other are 2Vdc. The advantage of having unequal DC sources is to produce various output levels. The circuit has 16 uni-directional switches and 6 bi-directional switches.

Each module generates 6 positive levels, 6 negative levels and one zero level so collectively from two modules the output consists of 12 positive levels, 12 negative levels and one zero level. The Fig 1 shows the circuit diagram of 25-level Multi-level Inverter. The pattern of switching of switches are selected to give less stress. Table 1 shows the switching table designed for the inverter.

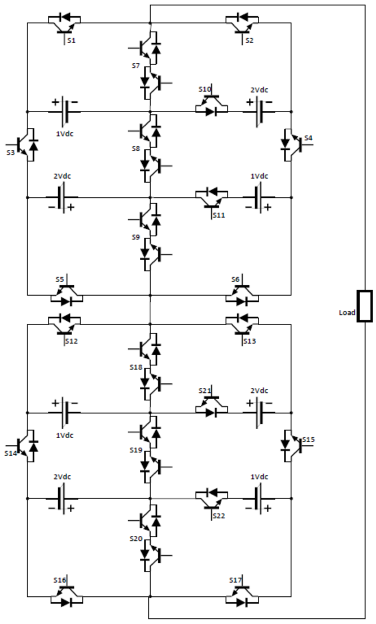

Fig 1 Circuit Diagram of 25-level Multi-level Inverter

Table 1 Switching Table for 25-level

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
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
7V	1	0	0	1	1	0	0	0	0	1	1
8V	1	0	0	1	1	0	0	0	0	1	1
9V	1	0	0	1	1	0	0	0	0	1	1
10V	1	0	0	1	1	0	0	0	0	1	1
11V	1	0	0	1	1	0	0	0	0	1	1
12V	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	1	1
-5V	0	1	1	0	0	0	0	0	1	0	0
-6V	0	1	1	0	0	1	0	0	0	1	1
-7V	0	1	1	0	0	1	0	0	0	1	1
-8V	0	1	1	0	0	1	0	0	0	1	1
-9V	0	1	1	0	0	1	0	0	0	1	1
-10V	0	1	1	0	0	1	0	0	0	1	1
-11V	0	1	1	0	0	1	0	0	0	1	1
-12V	0	1	1	0	0	1	0	0	0	1	1
	S12	**S13**	**S14**	**S15**	**S16**	**S17**	**S18**	**S19**	**S20**	**S21**	**S22**

0V	0	0	0	0	0	0	1	1	1	0	0
1V	0	0	0	0	0	0	1	1	1	0	0
2V	0	0	0	0	0	0	1	1	1	0	0
3V	0	0	0	0	0	0	1	1	1	0	0
4V	0	0	0	0	0	0	1	1	1	0	0
5V	0	0	0	0	0	0	1	1	1	0	0
6V	0	0	0	0	0	0	1	1	1	0	0
7V	1	0	0	0	0	0	0	1	1	0	0
8V	0	0	0	0	1	0	1	1	0	0	0
9V	1	0	0	0	1	0	0	1	0	0	0
10V	1	0	0	1	0	0	0	0	1	1	1
11V	0	0	0	1	1	0	1	0	0	1	1
12V	1	0	0	1	1	0	0	0	0	1	1
-1V	0	0	0	0	0	0	1	1	1	0	0
-2V	0	0	0	0	0	0	1	1	1	0	0
-3V	0	0	0	0	0	0	1	1	1	0	0
-4V	0	0	0	0	0	0	1	1	1	0	0
-5V	0	0	0	0	0	0	1	1	1	0	0
-6V	0	0	0	0	0	0	1	1	1	0	0
-7V	0	0	1	0	1	0	0	0	0	0	0
-8V	1	0	1	0	0	0	1	0	1	0	0
-9V	0	0	1	0	0	0	1	0	1	0	0
-10V	0	0	1	0	0	1	0	0	1	0	1
-11V	0	1	1	0	0	0	0	0	1	1	0
-12V	0	1	1	0	0	1	0	0	1	1	1

III.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 α1, α2, α3……. αm-2, αm-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):

α1, α2, α3………, α(m-1)/2 …………. (1)

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

α(m+1)/2=Π-α(m-1)/2, Π- α(m-2)/2 ……. Π-α1 ....(2)

The switching angles in third quadrant of the sine wave (i.e.,180º to 270º) are

αm=Π+α1…..., Π+α(m-1)/2 ……………. (3)

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

α(3m-1)/2=2Π-α(m-1)/2………2Π-α1 …………… (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.

3.1. Equal 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=7.2º, α2=14.4º, α3=21.6º, α4=28.8º, α5=36º

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.

3.2 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=6.92º, α2=13.84º, α3=20.769º, α4=27.69º, α5=34.61º 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.

3.3 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=2.38º, α2=7.18º α3=12.02º, α4=16.95º, α5=22. 02º α1=1.19º, α2=3.59º, α3=6.01º, α4=8.47º, α5=11.01º 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.

3.4Half 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=14.4º 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 2 Switching Angles of Equal Phase Method

	Switching Angles		Switching Angles		Switching Angles		Switching Angles
α0	0	α13	93.6	α26	187.2	α39	280.8
α1	7.2	α14	100.8	α27	194.4	α40	288
α2	14.4	α15	108	α28	201.6	α41	295.2
α3	21.6	α16	115.2	α29	208.8	α42	302.4
α4	38.8	α17	122.4	α30	216	α43	309.6
α5	36	α18	129.6	α31	223.2	α44	316.8
α6	43.2	α19	136.8	α32	230.4	α45	324
α7	50.4	α20	144	α33	237.6	α46	331.2
α8	57.6	α21	151.2	α34	244.8	α47	338.4
α9	64.8	α22	158.4	α35	252	α48	345.6
α10	72	α23	165.6	α36	259.2	α49	352.8
α11	79.2	α24	172.8	α37	266.4	α50	360
α12	86.4	α25	180	α38	273.6		

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Table 3 Switching Angles of Half Equal Phase Method

	Switching Angles		Switching Angles		Switching Angles		Switching Angles
α0	0	α13	96.92	α26	186.92	α39	283.84
α1	6.92	α14	103.84	α27	193.84	α40	290.76
α2	13.84	α15	110.76	α28	200.76	α41	297.69
α3	20.76	α16	117.69	α29	207.69	α42	304.61
α4	27.69	α17	124.61	α30	214.61	α43	311.53
α5	34.61	α18	131.53	α31	221.53	α44	318.46
α6	41.53	α19	138.46	α32	228.46	α45	325.38
α7	48.46	α20	145.38	α33	235.38	α46	332.30
α8	55.38	α21	152.30	α34	242.30	α47	339.23
α9	62.30	α22	159.23	α35	249.23	α48	346.15
α10	69.23	α23	166.15	α36	256.15	α49	353.07
α11	76.15	α24	173.07	α37	263.07	α50	360
α12	83.07	α25	180	α38	276.92		

Table 4 Switching Angles of Half Height Method

	Switching Angles		Switching Angles		Switching Angles		Switching Angles
α0	0	α13	143.29	α26	181.19	α39	329.47
α1	1.19	α14	149.47	α27	183.59	α40	333.82
α2	3.59	α15	153.8	α28	186.01	α41	337.45
α3	6.01	α16	157.45	α29	188.47	α42	340.65
α4	8.47	α17	160.65	α30	191.01	α43	343.60
α5	11.01	α18	163.60	α31	193.63	α44	346.36
α6	13.63	α19	166.36	α32	196.39	α45	348.98
α7	16.39	α20	168.98	α33	199.34	α46	351.52
α8	19.34	α21	171.52	α34	202.54	α47	353.98
α9	22.54	α22	173.98	α35	206.17	α48	356.40
α10	26.17	α23	176.40	α36	210.52	α49	358.80
α11	30.52	α24	178.80	α37	216.70	α50	360
α12	36.70	α25	180	α38	323.29		

Table 5 Switching Angles of Half Height Method

	Switching Angles		Switching Angles		Switching Angles		Switching Angles
α0	0	α13	106.59	α26	182.38	α39	298.95
α1	2.38	α14	118.95	α27	187.18	α40	307.65
α2	7.18	α15	127.65	α28	192.02	α41	314.90
α3	12.02	α16	134.90	α29	196.95	α42	321.31
α4	16.95	α17	141.31	α30	202.02	α43	327.20
α5	22.02	α18	147.20	α31	207.27	α44	332.72
α6	27.27	α19	152.72	α32	212.79	α45	337.97
α7	32.79	α20	157.97	α33	218.68	α46	343.04
α8	38.68	α21	163.04	α34	225.09	α47	347.97
α9	45.09	α22	167.97	α35	232.34	α48	352.81
α10	52.34	α23	172.81	α36	241.04	α49	357.61
α11	61.04	α24	177.61	α37	253.40	α50	362.38
α12	73.40	α25	180	α38	286.59		

TABLE 6 Specifications of 25-level Inverter

Specifications of proposed 25-level MLI
V1 = V4 =V5 = V8 = 30V V2 = V3 =V6 = V7 = 60V
R load = R=25.45 Ω
RL load = R=20.36 Ω & L = 48.61mH

IV.SIMULATION OF PROPOSED CIRCUIT & DICUSSION OF RESULTS

Fig 2 shows the Simulink model of 25-level multi-level inverter. To check the performance of proposed 25-level Asymmetrical MLI to generate 25 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 25 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 25-level Inverter

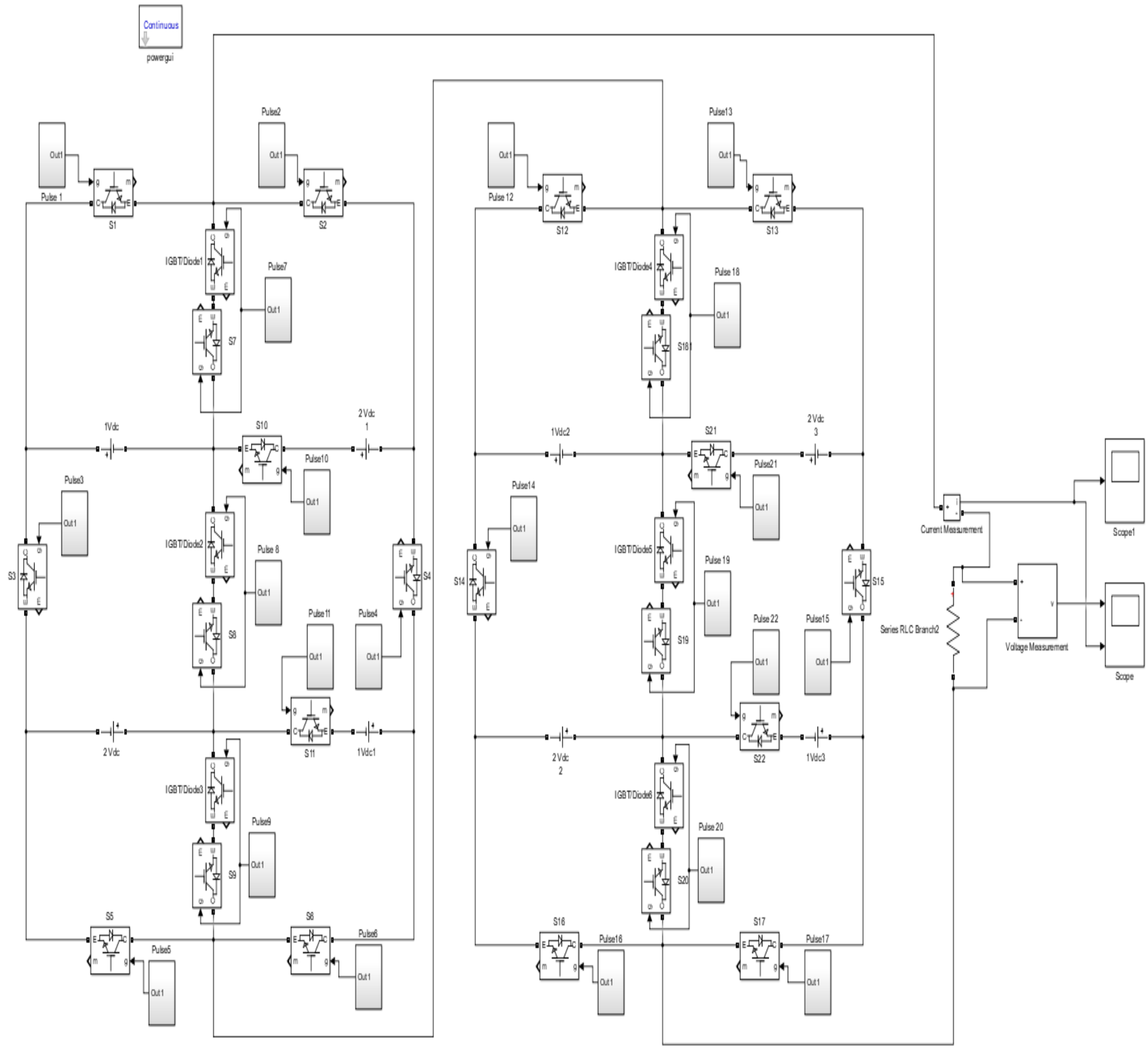
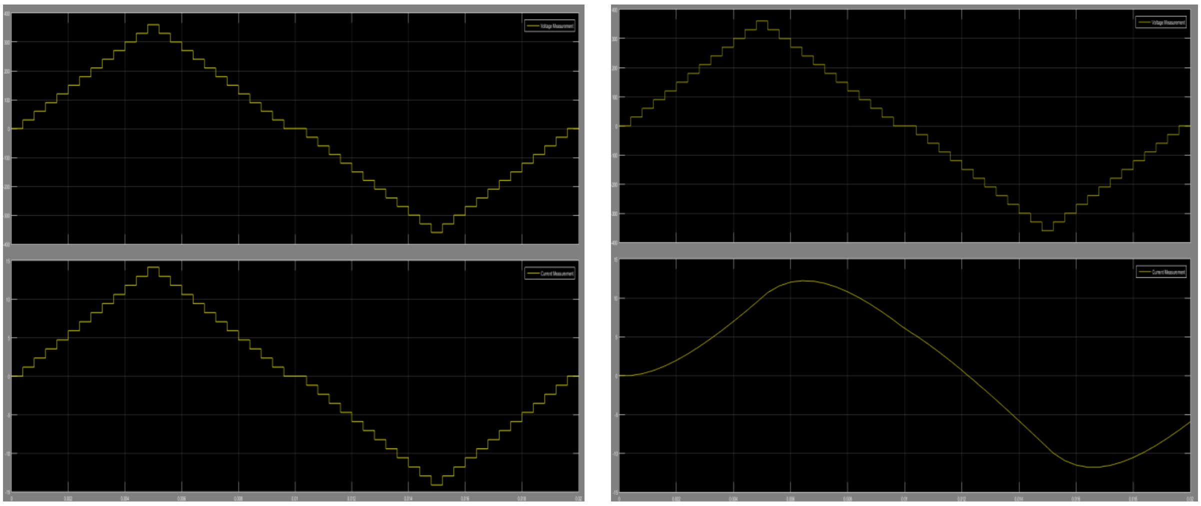


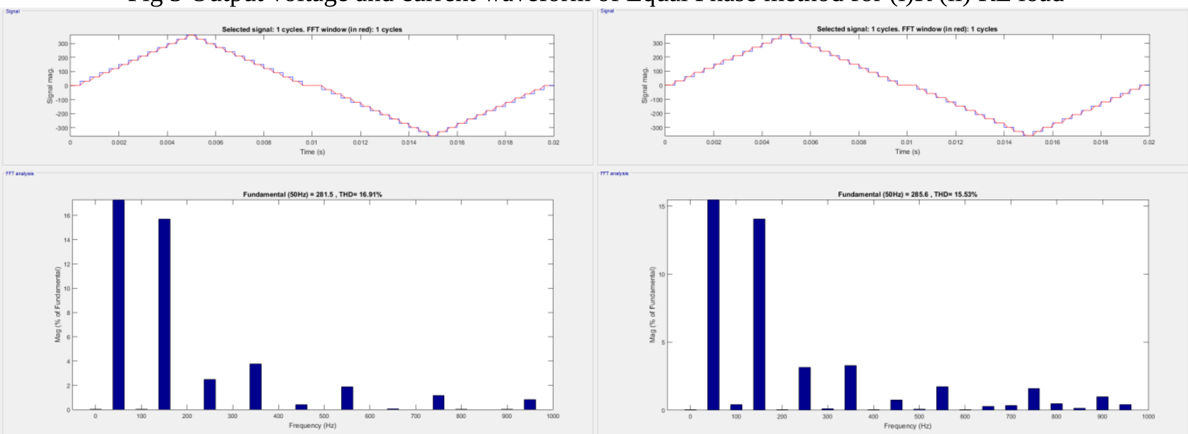
Fig 2 Simulation model of 25-level MLI

Fig 3 shows the output voltage and current waveform for R and RL load using Equal Phase Control technique. Fig 4 shows the FFT analysis of the 25-level inverter for R and RL load using Equal Phase Control technique.



(i) (ii)

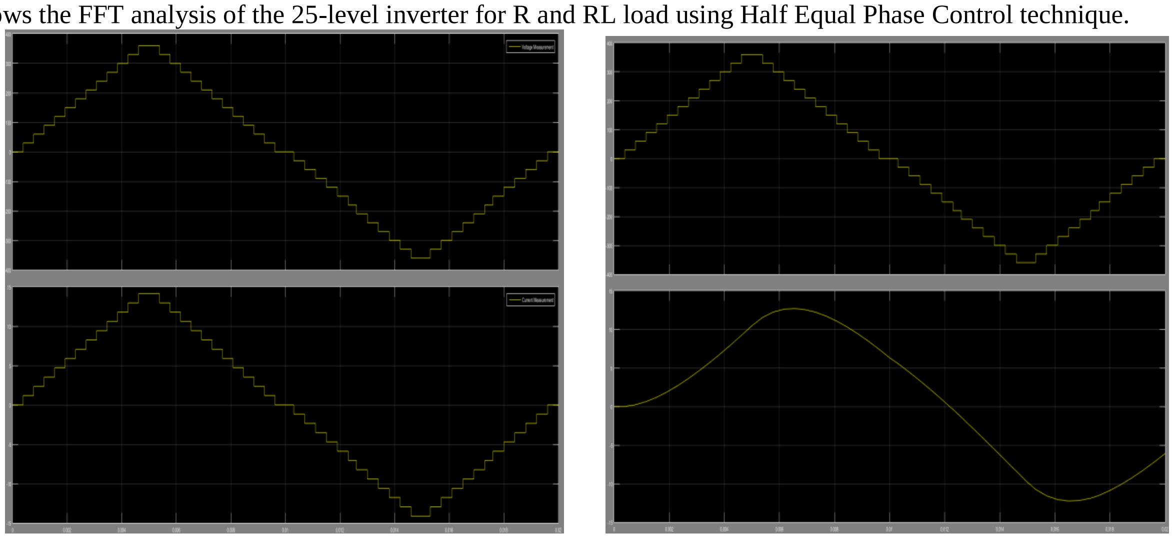
Fig 3 Output voltage and current waveform of Equal Phase method for (i)R (ii) RL load



(i) (ii)

Fig 4 shows the FFT analysis window of Equal Phase method for (i)R (ii)RL load.

Fig 5 shows the output voltage and current waveform for R and RL load using Half Equal Phase Control technique. Fig 6 shows the FFT analysis of the 25-level inverter for R and RL load using Half Equal Phase Control technique.



(i) (ii)

Fig 5 Output voltage and current waveform of Half Equal Phase method for (i)R (ii) RL load

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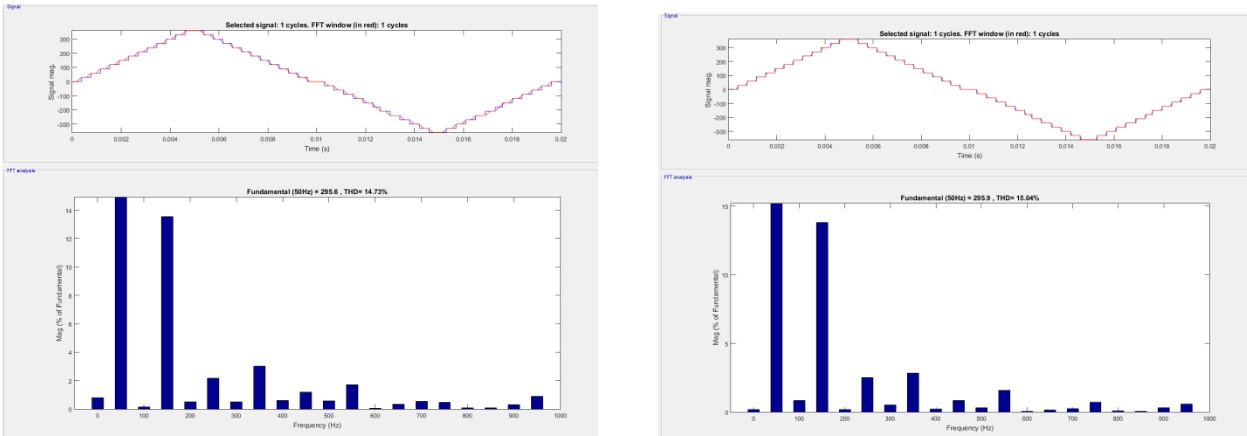
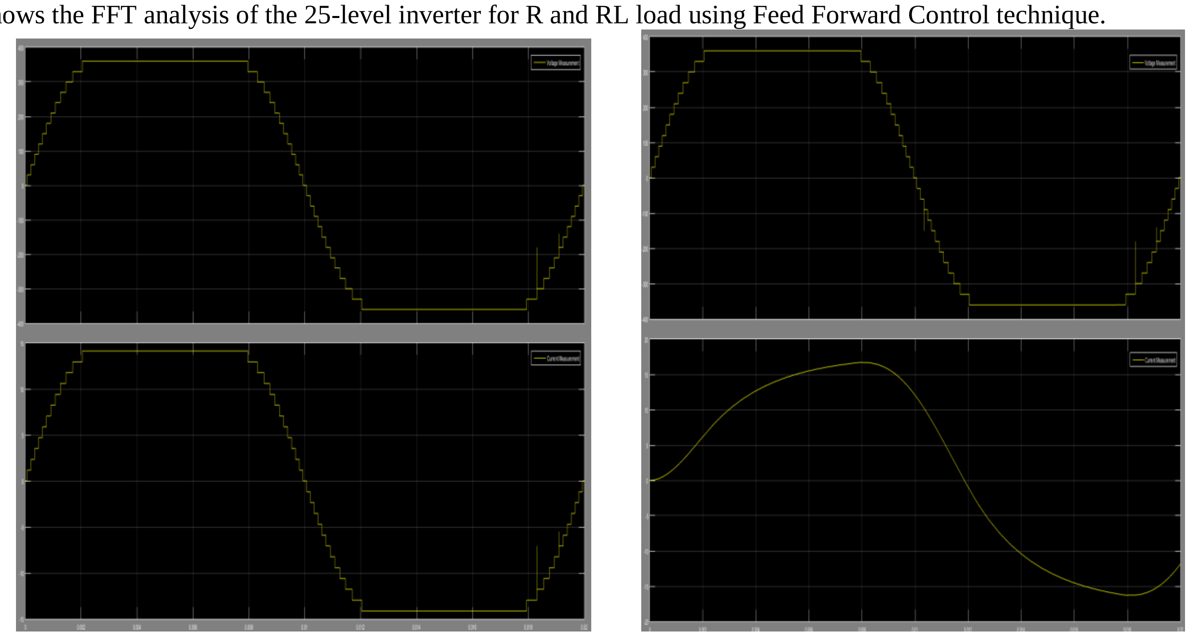


(i) (ii)

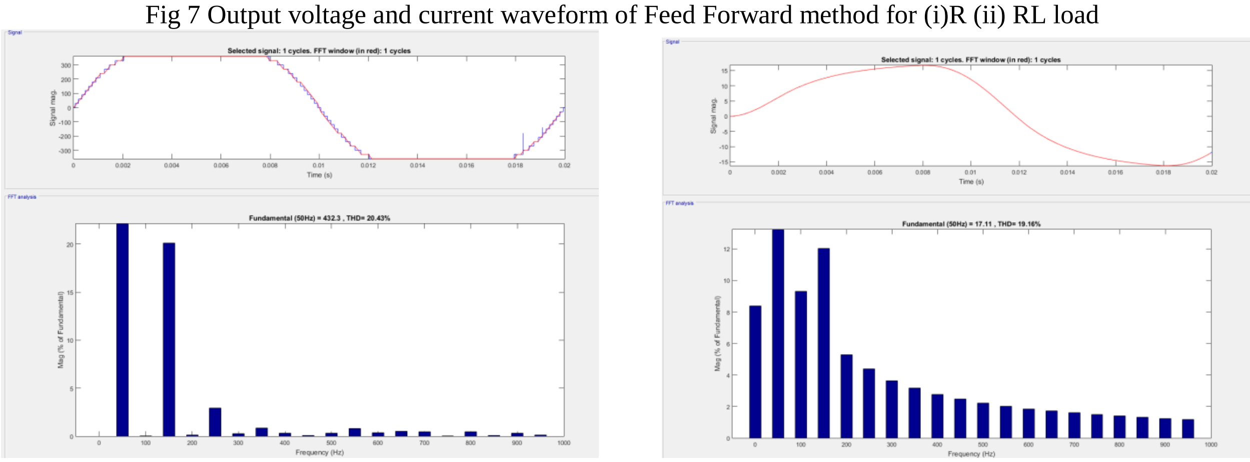
Fig 6 shows the FFT analysis window of Half Equal Phase method for (i)R (ii)RL load

Fig 7 shows the output voltage and current waveform for R and RL load using Half Equal Phase Control technique. Fig 8 shows the FFT analysis of the 25-level inverter for R and RL load using Feed Forward Control technique.



(i) (ii)

Fig 7 Output voltage and current waveform of Feed Forward method for (i)R (ii) RL load



(i) (ii)

Fig 8 shows the FFT analysis window of Feed Forward method for (i)R (ii)RL load

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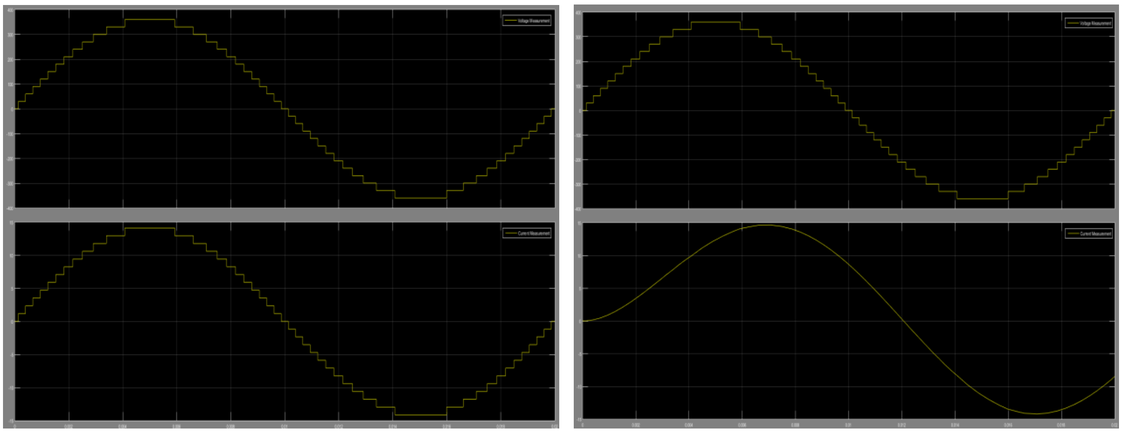
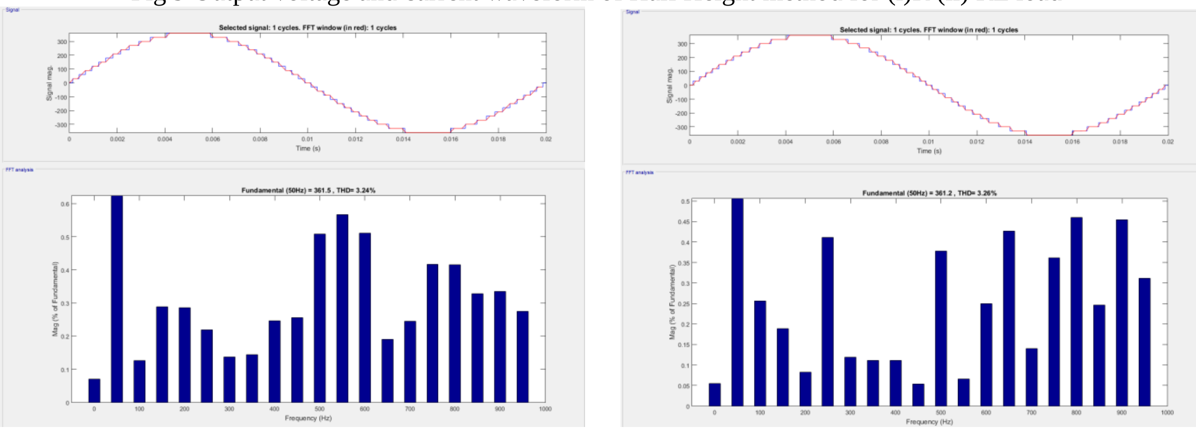
Fig 9 shows the output voltage and current waveform for R and RL load using Half Equal Phase Control technique. Fig 10 shows the FFT analysis of the 25-level inverter for R and RL load using Feed Forward Control technique.



(i) (ii)

Fig 9 Output voltage and current waveform of Half Height method for (i)R (ii) RL load



(i) (ii)

Fig 10 shows the FFT analysis window of Half Height method for (i)R (ii)RL load

Table 5 Comparison of control techniques with respect to THD

Control Techniques	Load voltage	THD%
	R Load	RL Load
Equal Phase Method	16.91%	15.53%
Half Equal Phase Method	14.73%	15.04%
Feed Forward Method	20.43%	19.16%
Half Height Method	3.24%	3.26%

V.CONCLUSION

The design and simulation of 25-level Asymmetrical Multi-level inverter for R load and RL load is simulated and analyzed. Among the four control techniques, Half-Height method gives less THD compared to other three control strategies. The obtained THD with Half-Height method is 3.24% for R load and 3.26% for RL load which satisfies IEEE519 standards.

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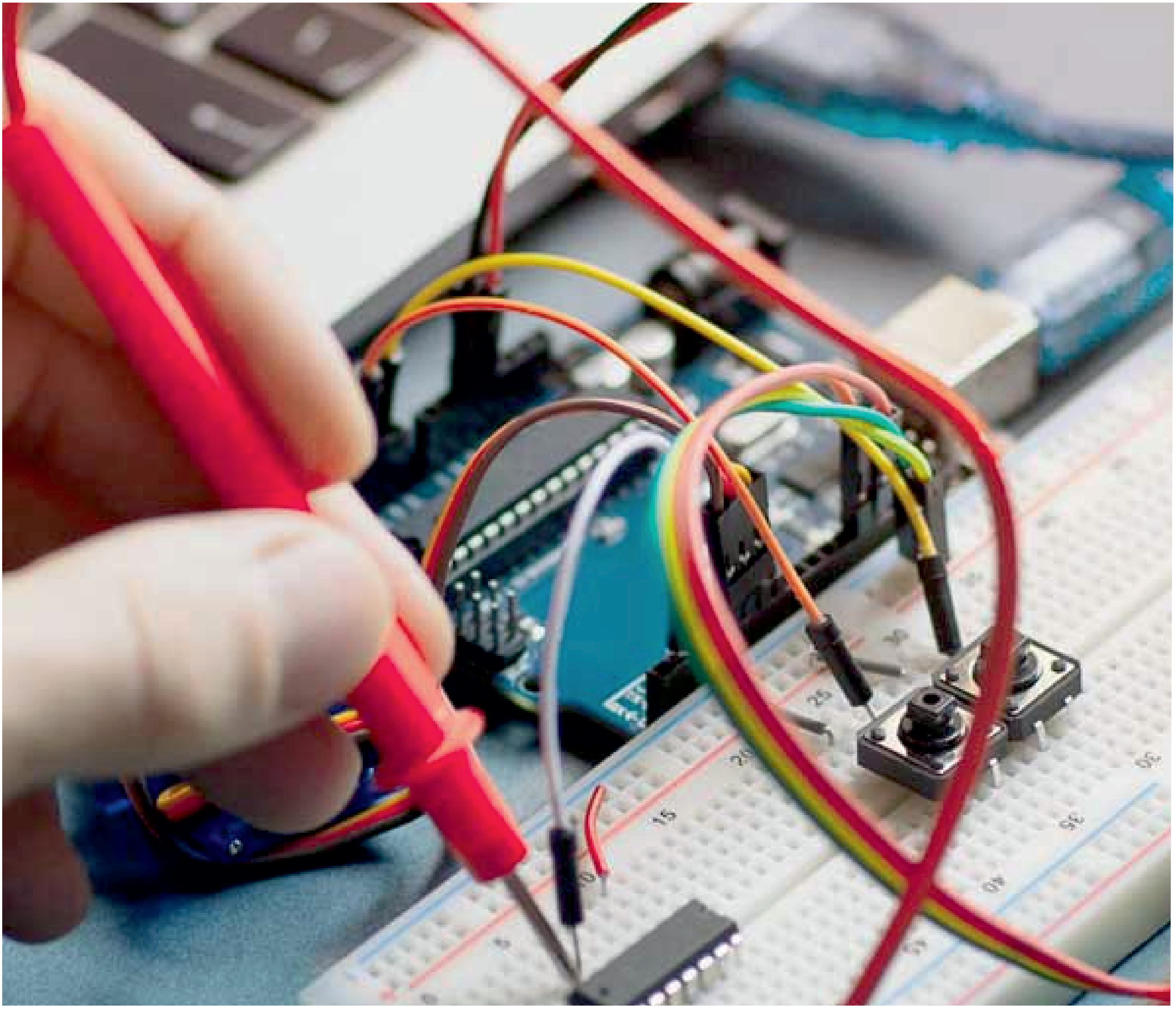
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