CHAPTER 8

EXPERIMENTAL RESULTS

In this chapter, results obtained from hardware implementation are compared with simulation results for selected scheme. Comparison is on basis of THD, output voltage obtained and fundamental voltage from FFT analysis. Hardware testing is done with lower as well as higher voltage. For lower voltage 12V batteries are taken as supply for single phase as well as three phase. Initially single leg is tested with and without modulation. Similar three cards are made and tested individually then three phase connections are done. In three phase output is obtained for different modulation techniques which have been already discussed in previous chapters. Modulation index is taken either 0.9 while frequency modulation index is 21.Control signals are applied using SIMULINK-CCS3.1-EMULATOR C2000 USB- DSP KIT 28335 as discussed in chapter 6.

Output is saved in DSO in .bmp and .csv extension. The file saved in .csv format is imported in MATLAB R2013a and then THD is found. Limitations of this method are: i) maximum 1024 points are saved ii) first half cycle output reconstructed from such points is not proper iii) maximum two cycles are obtained from points saved in .csv format.

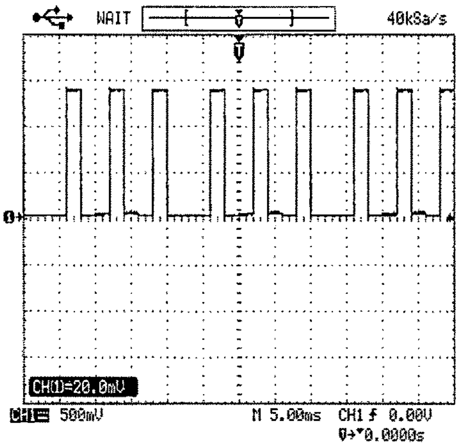
Further sections describe different outputs for various ratings of voltage and current with different gating pulses for selected configuration of single phase and three phase HMLI.

8.1 HARDWARE RESULTS FOR SINGLE PHASE HYBRID MULTILEVEL INVERTER

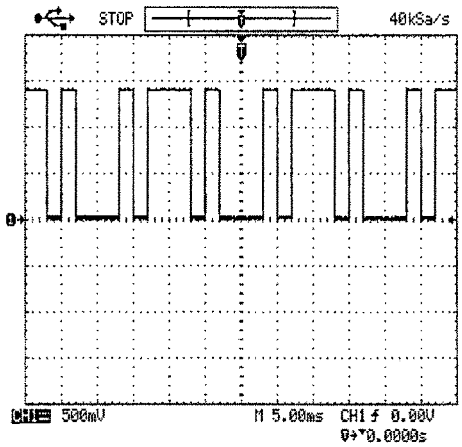
Single phase hybrid multilevel inverter is tested on 12V batteries and respective five level output is obtained. Output is taken for R and R-L load.

8.1.1 HARDWARE OUTPUT FOR SINGLE PHASE HMLI WITHOUT MODULATION

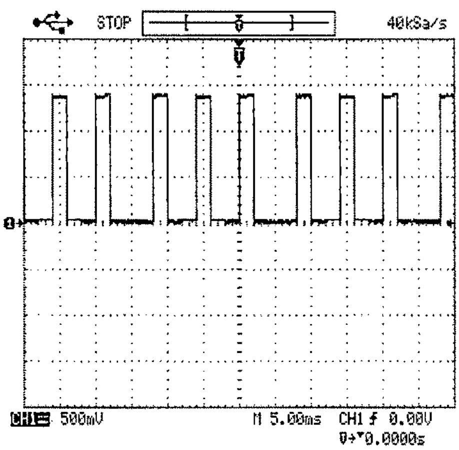
Fig 8.1 shows control signals for six switches. Fig 8.2 shows five level output 220 Ω-½ Watt resistor connected as load. Fig. 8.3 is THD obtained from .csv file imported to MATLAB.



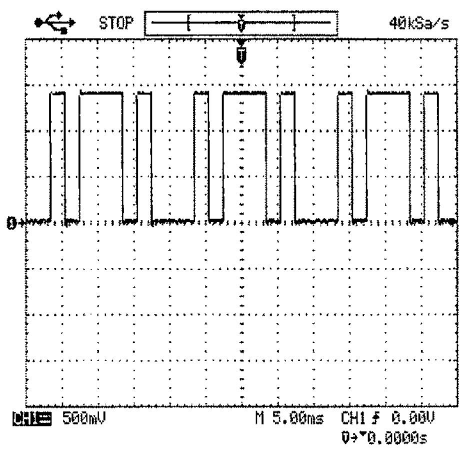
(a) G_1



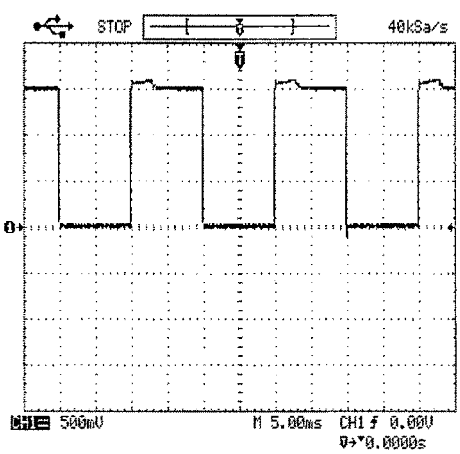
(b) G_2



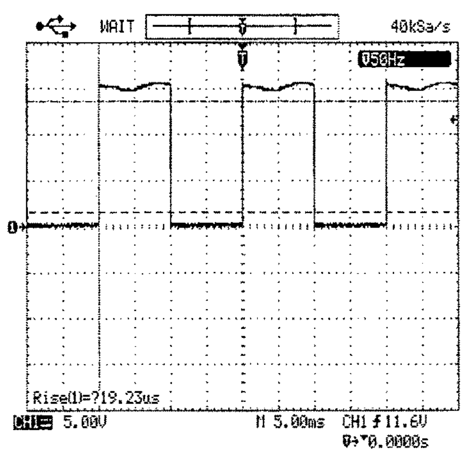
(c) G_3



(d) G_4



(e) G_5



(f) G_6

Fig. 8.1 Control signals for single phase HMLI without modulation

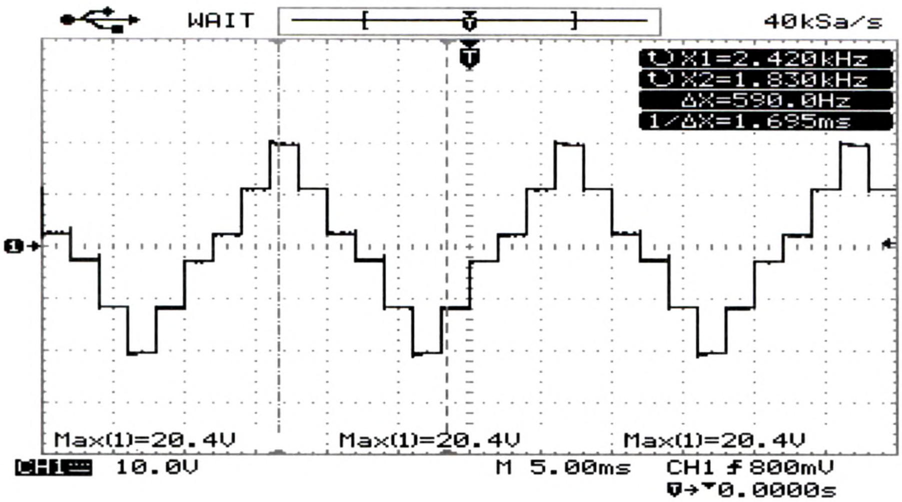


Fig. 8.2 Five level output for single phase HMLI without modulation

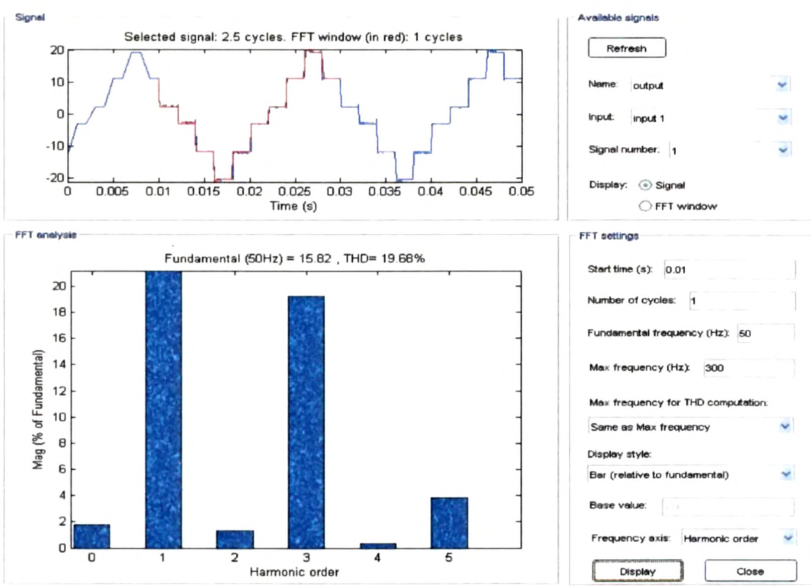
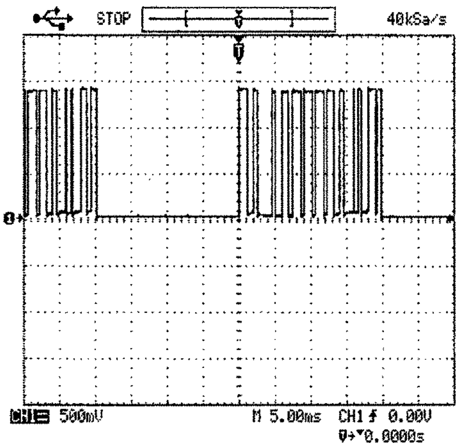


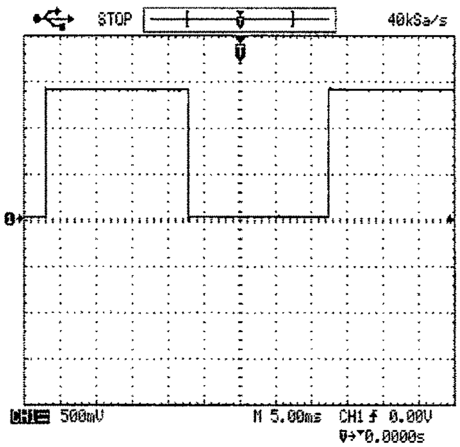
Fig. 8.3 FFT analysis and THD for single phase HMLI without modulation

8.1.2 HARDWARE OUTPUT FOR SINGLE PHASE HMLI WITH PD MODULATION TECHNIQUE

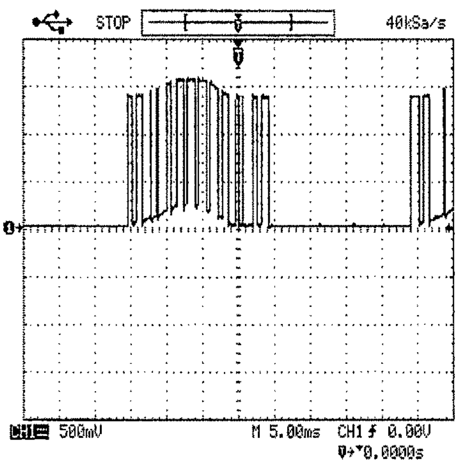
Fig 8.4 shows control signals for six switches. Fig 8.5 (a) shows five level output across 220 Ω- 1 Watt resistive load. Fig 8.5 (b) shows five level output across R-L load. Fig. 8.6 shows current through RL load for single phase HMLI with PD modulation technique. Fig 8.7 (a) is five level output with FFT for R load as mentioned above. Control signals are given at sample rate of 10 kHz which is changed to 100 kHz for better resolution as shown in Fig 8.7 (b). Fig. 8.8 is THD obtained from .csv file imported to MATLAB. Fig. 8.9 shows similar output for second card.



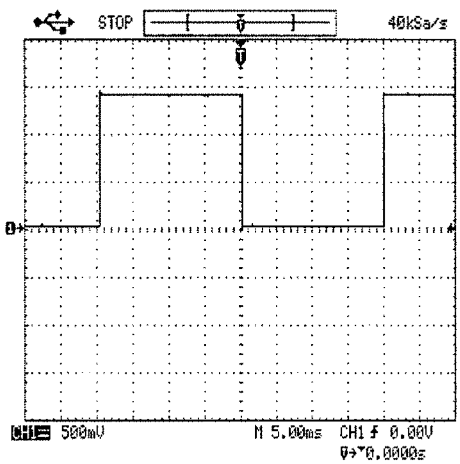
(a) G_1



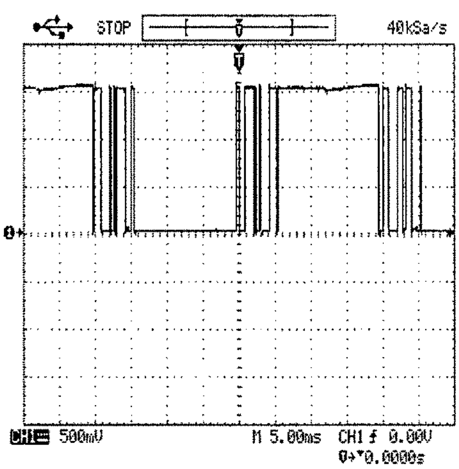
(b) G_2



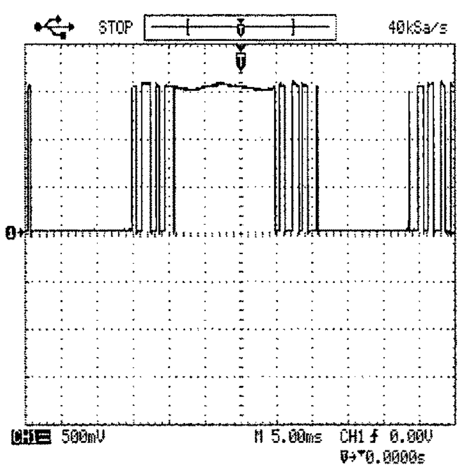
(c) G_3



(d) G_4

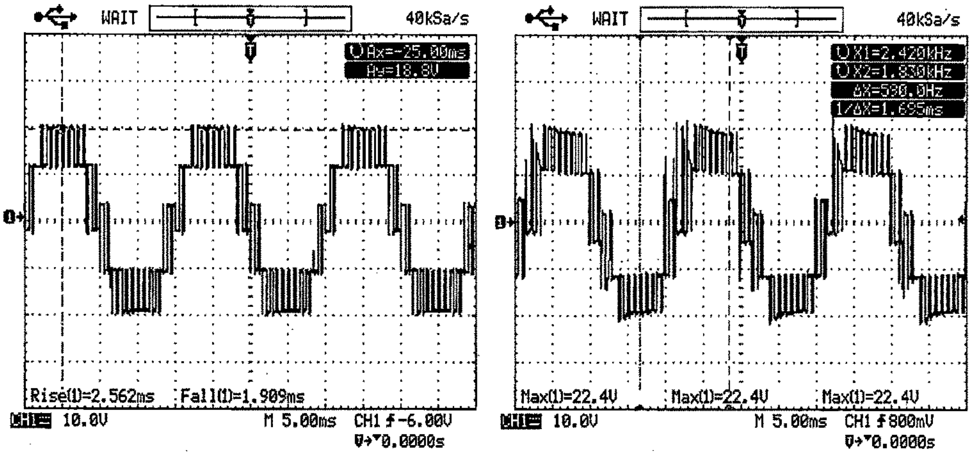


(e) G_5



(f) G_6

Fig. 8.4 Control signals for single phase HMLI with PD modulation technique



(a) R load (b) R-L load

Fig. 8.5 Single phase HMLI output with PD modulation technique

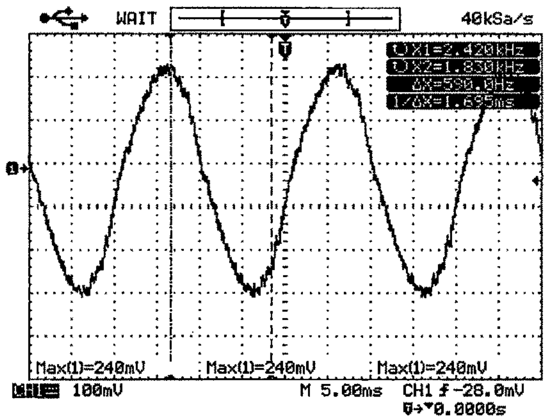
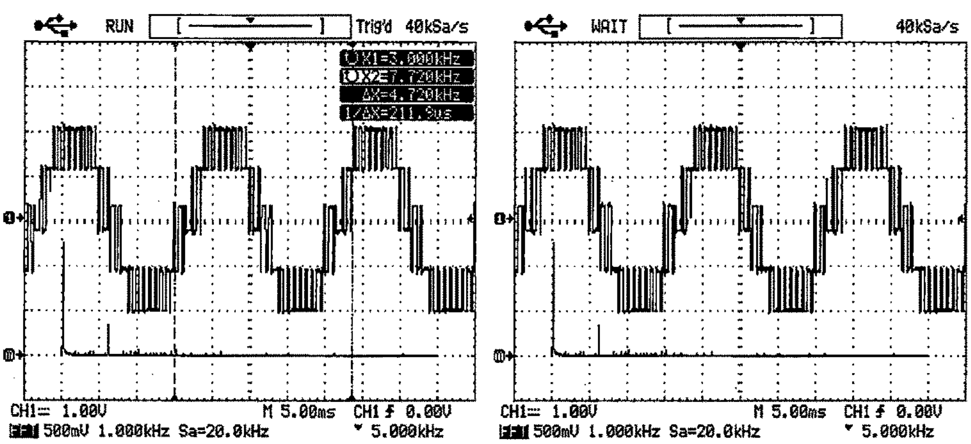


Fig. 8.6 Current through RL load for single phase HMLI with PD modulation technique



(a) Sample rate=10 kHz (b) Sample rate=100 kHz

Fig. 8.7 Single phase HMLI output and FFT with PD modulation technique for R load

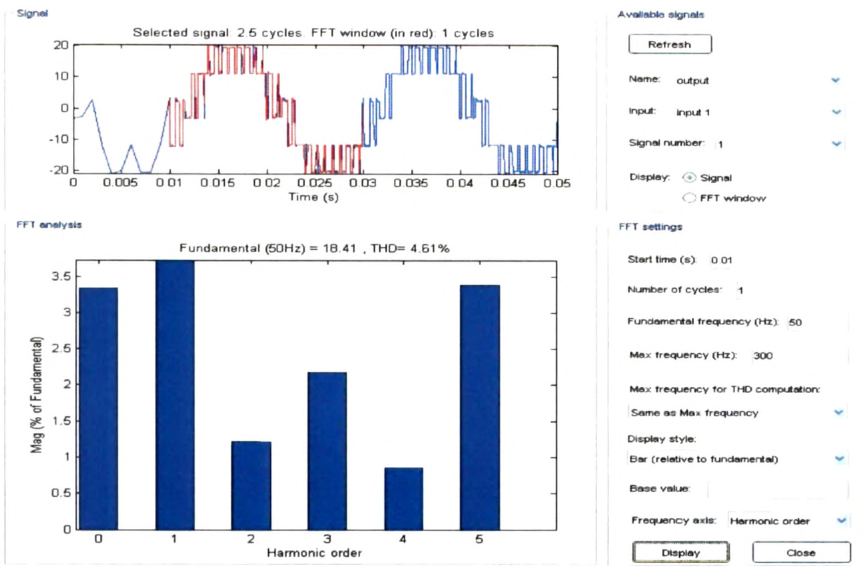


Fig. 8.8 FFT analysis and THD for single phase HMLI with PD modulation technique

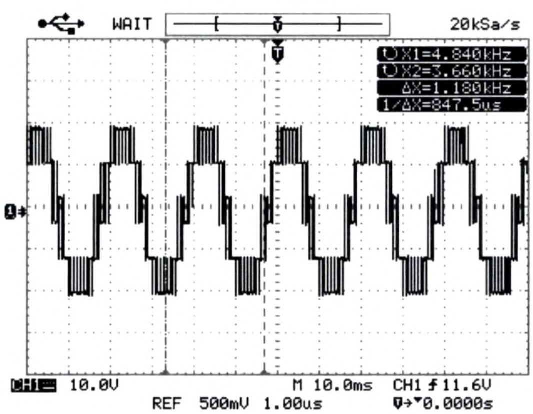


Fig. 8.9 Single phase HMLI output with PD modulation technique for R load

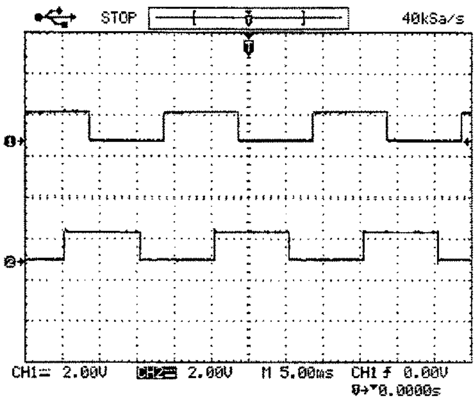
8.2 HARDWARE RESULTS FOR THREE PHASE HYBRID MULTILEVEL INVERTER

Three phase hybrid multilevel inverter is tested on 12V batteries and as discussed in chapter 7 DC supply for three phase inverter is double the H bridge supply hence two batteries in series are connected. Testing is also done with regulated power supplies of value 80V and 40V. Output is measured across resistive load in star configuration. Control signals are phase shifted by 120^0. Different modulation techniques are applied.

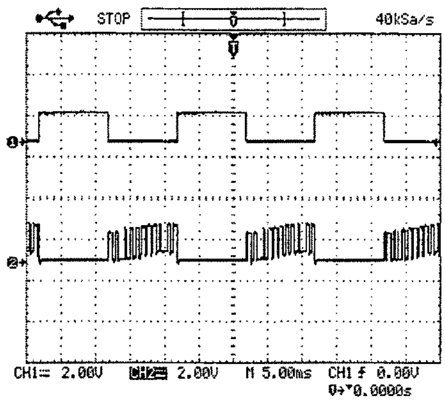
8.2.1 HARDWARE OUTPUT FOR THREE PHASE HMLI WITH PD MODULATION TECHNIQUE

i) BATTERIES AS SUPPLY

Fig 8.10(a) shows control signals with PD modulation technique for switches of card 1 and card 2 which are 120^0 apart.

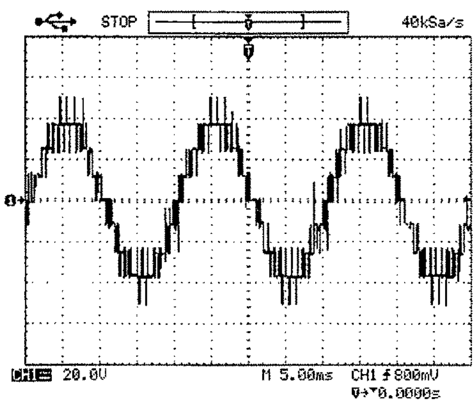


(a) G_2 G_2'

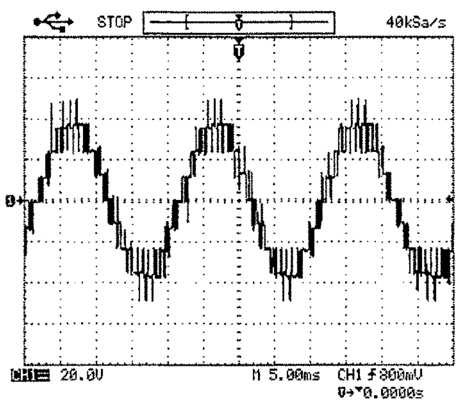


(b) G_2 G_3

Fig. 8.10 Control signals for three phase HMLI with PD modulation technique

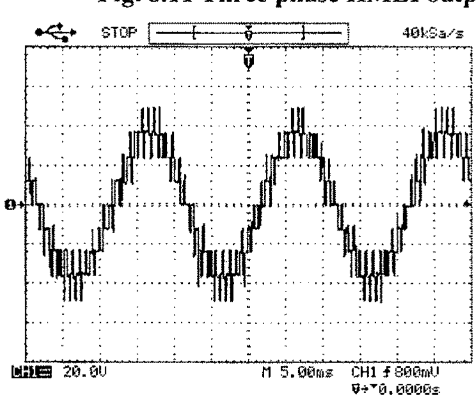


(a) v_{RY}

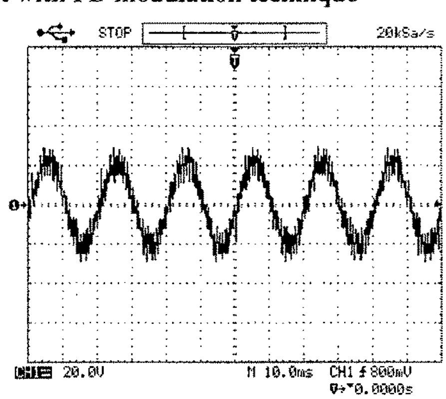


(b) v_{YB}

Fig. 8.11 Three phase HMLI output with PD modulation technique



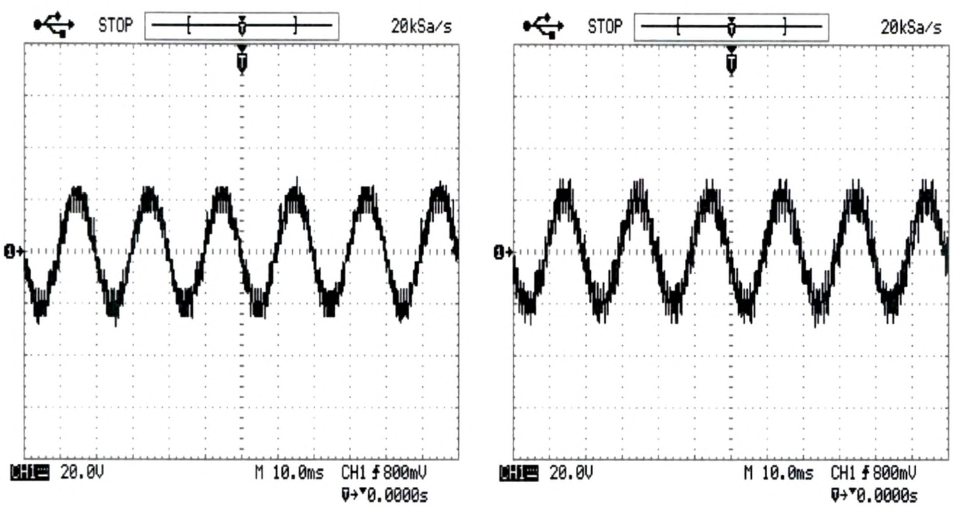
(a) v_{RB}



(b) v_R

Fig. 8.12 Three phase HMLI output with PD modulation technique

Fig 8.11(a) shows 9 level line to line output voltage(v_{RY}). 100 Ω-1W resistors are star connected as load. Fig 8.11(b) output voltage v_{YB}. Fig 8.12 (a) output voltage v_{RB}. Fig 8.12(b) shows 7 level v_R output voltage while Fig 8.13(a) and (b) shows 7 level output voltage v_Y and v_B respectively. Control signals were given at sample rate of 25 kHz due to limitation of MATLAB SIMULINK. Fig. 8.14 shows THD obtained from .csv file imported to MATLAB for one output and other values are mentioned in Table 8.1.



(a) v_Y **(b) v_B phase**

Fig. 8.13 Three phase HMLI output with PD modulation technique

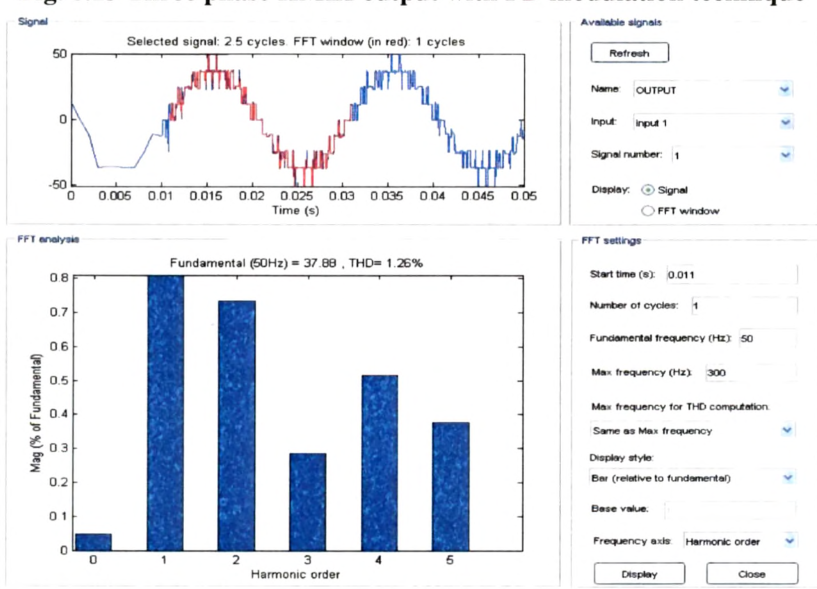
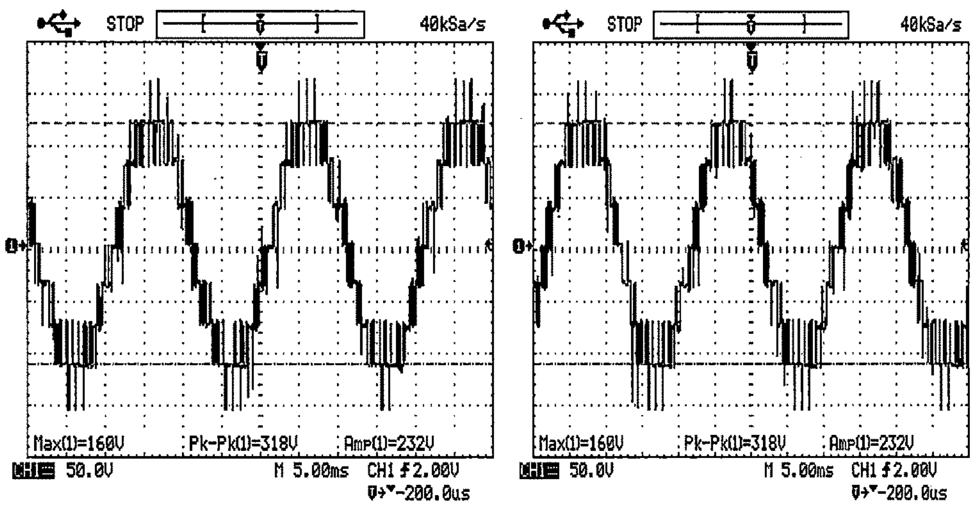


Fig. 8.14 FFT analysis and THD for 3 phase HMLI with PD modulation technique

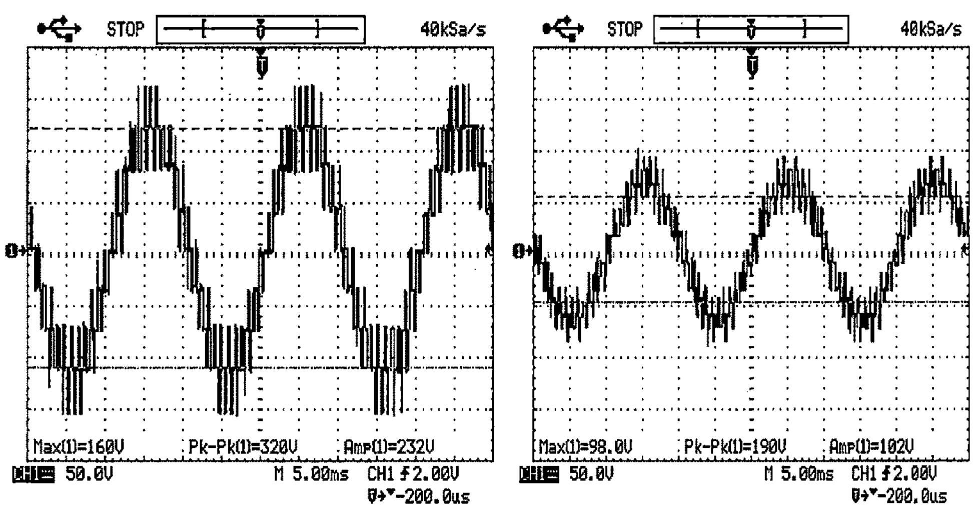
ii) REGULATED POWER SUPPLY

Fig 8.15(a) and (b) shows 9 level line to line output voltage v_{RY} and v_{YB} respectively. Three 1 kΩ- 10 W resistors are connected in parallel to obtain equivalent resistor of 330 Ω which are star connected as load. Fig 8.16 (a) output voltage v_{RB} and Fig 8.16 (b) shows 7 level v_B phase output voltage. Control signals were given at sample rate of 25 kHz due to limitation of MATLAB SIMULINK. Fig. 8.17 is THD obtained from .csv file imported to MATLAB for one output and other values are mentioned in Table 8.1.



(a) v_{RY} (b) v_{YB}

Fig. 8.15 Three phase HMLI output with PD modulation technique 330 Ω



(a) v_{RB} (b) v_B

Fig. 8.16 Three phase HMLI output with PD modulation technique 330 Ω

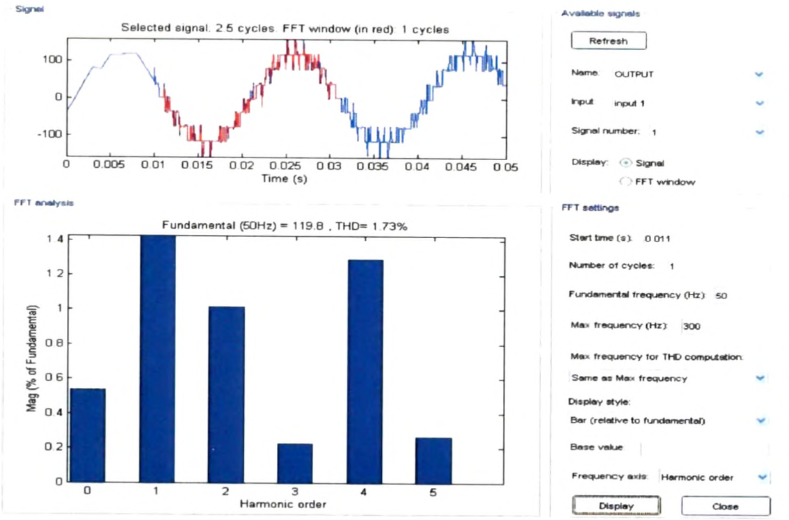
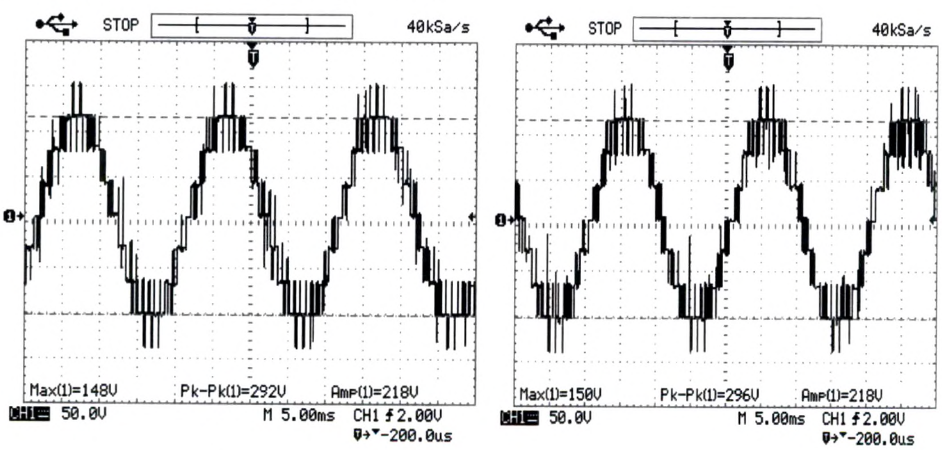


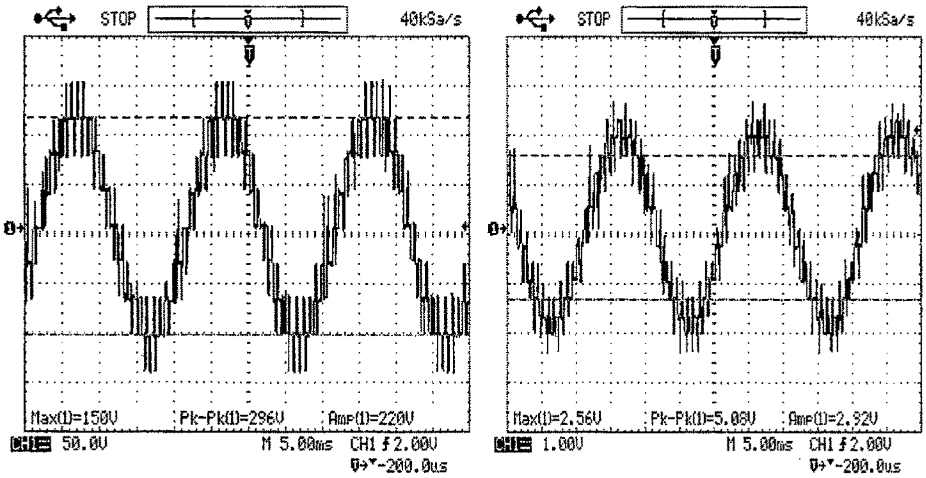
Fig. 8.17 FFT analysis and THD for three phase Line to line voltage for RY 330Ω star load

Fig 8.18 (a) shows 9 level line to line output voltage(v_{RY}). 33Ω- 1000 W heater coil are star connected as load. Fig 8.18 (b) shows output voltage v_{YB}. Fig 8.19 (a) shows output voltage v_{RB}. Control signals were given at sample rate of 25 KHz due to limitation MATLAB SIMULINK. Fig. 8.21 is THD obtained from .csv file imported to MATLAB for one output and other values are mentioned in Table 8.1. Fig. 8.19 (b) shows output current i_R measured across 1Ω resistor connected in series with load. Fig. 8.20(a) and (b) show output current i_Y and i_B respectively.



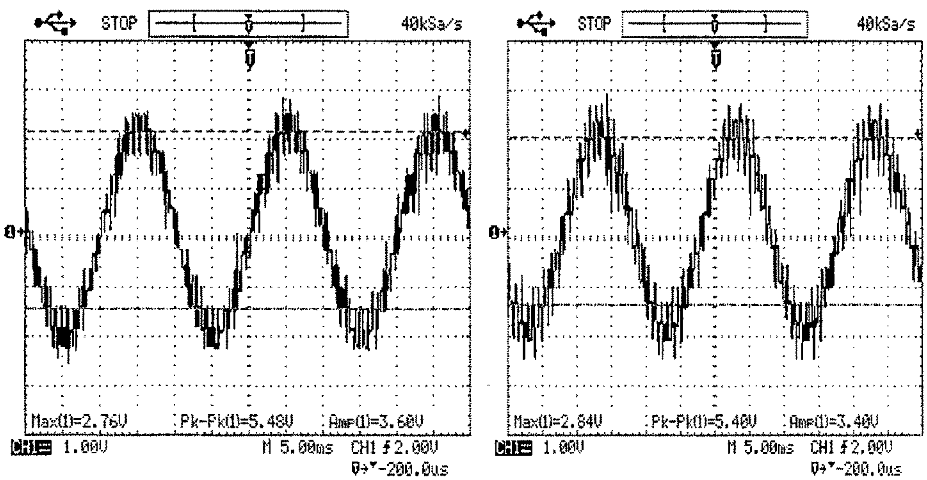
(a) v_{RY} (b) v_{YB}

Fig. 8.18 Three phase HMLI output with PD modulation technique 33Ω



(a) v_{RB} (b) i_R

Fig. 8.19 Output voltage and current for Three phase HMLI with PD modulation technique



(a) i_Y (b) i_B

Fig. 8.20 Output current for three phase HMLI with PD modulation

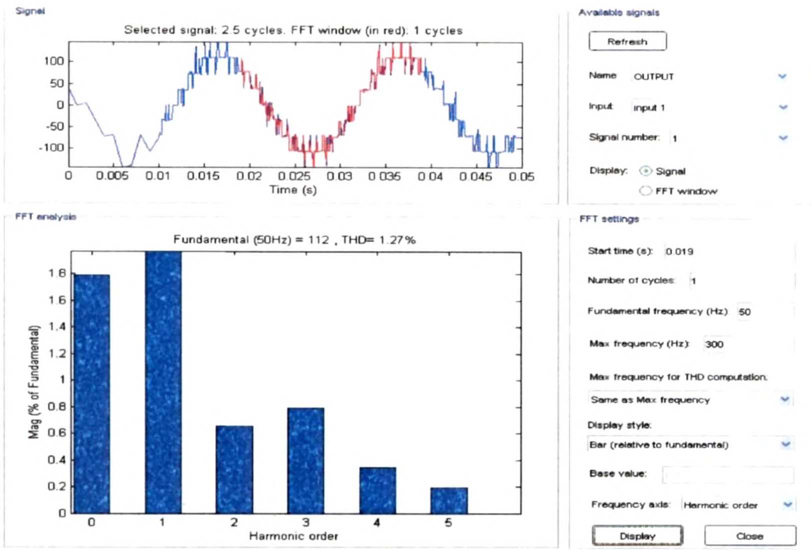
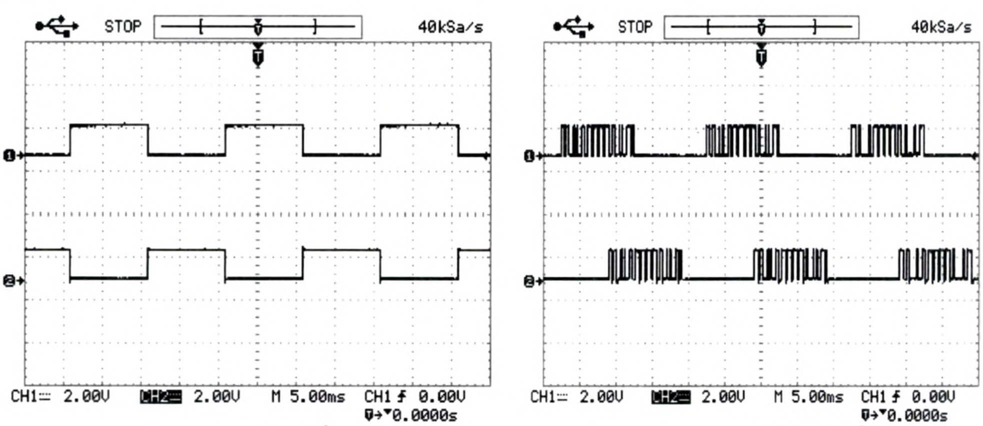


Fig. 8.21 FFT analysis and THD for 3 phase HMLI with PD modulation technique

8.2.2 HARDWARE OUTPUT FOR THREE PHASE HMLI WITH POD MODULATION TECHNIQUE

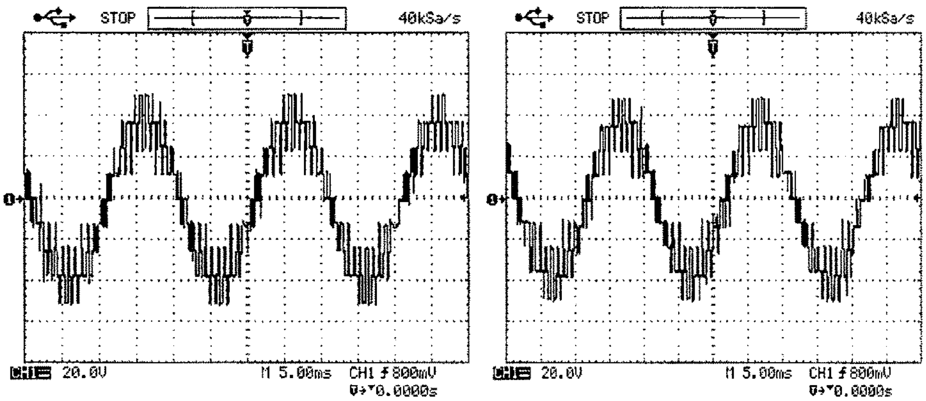
i) BATTERIES AS SUPPLY

Fig 8.22(b) shows control signals with POD modulation technique for switches of card 1 and card 2 which are 120^0 apart. Fig 8.23(a) shows 9 level line to line output voltage(v_{RY}). 100 Ω- 1 W resistors are star connected as load. Fig 8.23(b) shows output line voltage. Fig 8.24 (a) output voltage v_{RB}. Fig 8.24 (b) shows 7 level v_R phase output voltage while Fig 8.25 (a) and (b) show 7 level phase voltage v_Y and v_B respectively. Control signals were given at sample rate of 25 kHz due to limitation of MATLAB SIMULINK.



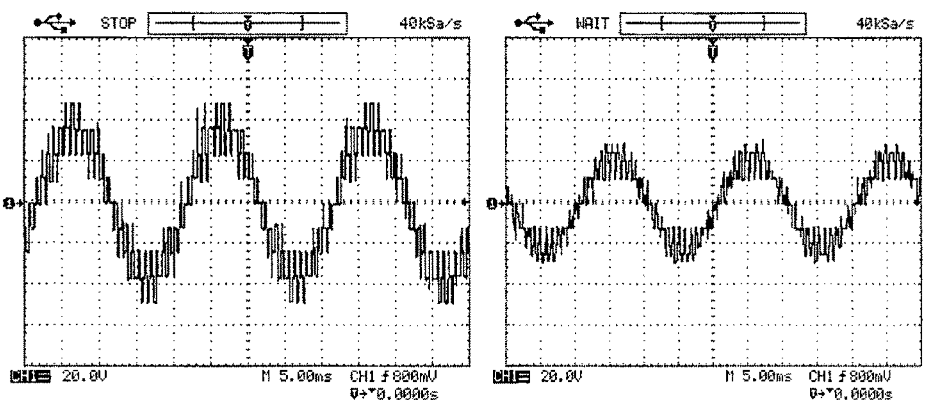
(a) G_2 G_2' (b) G_3 G_3'

Fig. 8.22 Control signals for three phase HMLI with POD modulation technique



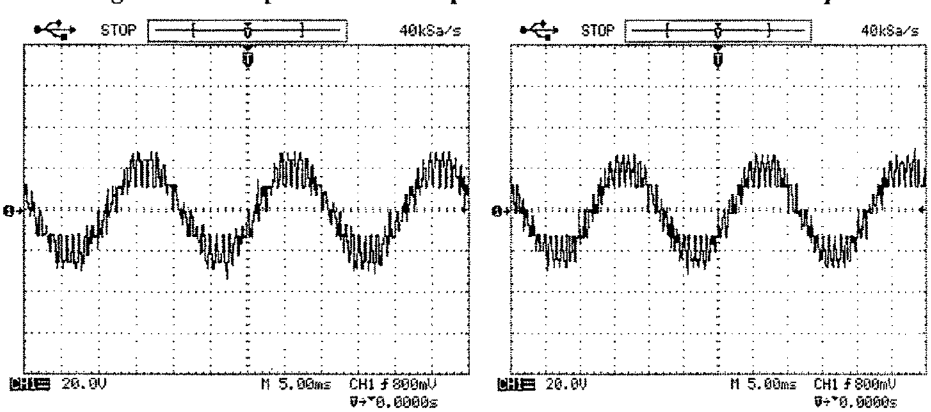
(a) v_{RY} **(b) v_{YB}**

Fig. 8.23 Three phase HMLI output voltage with POD modulation technique



(a) v_{RB} **(b) v_{R}**

Fig. 8.24 Three phase HMLI output with POD modulation technique



(a) v_{Y} **(b) v_{B}**

Fig. 8.25 Three phase HMLI output with POD modulation technique

Fig. 8.26 is THD obtained from .csv file imported to MATLAB for one output and other values are mentioned in Table 8.1.

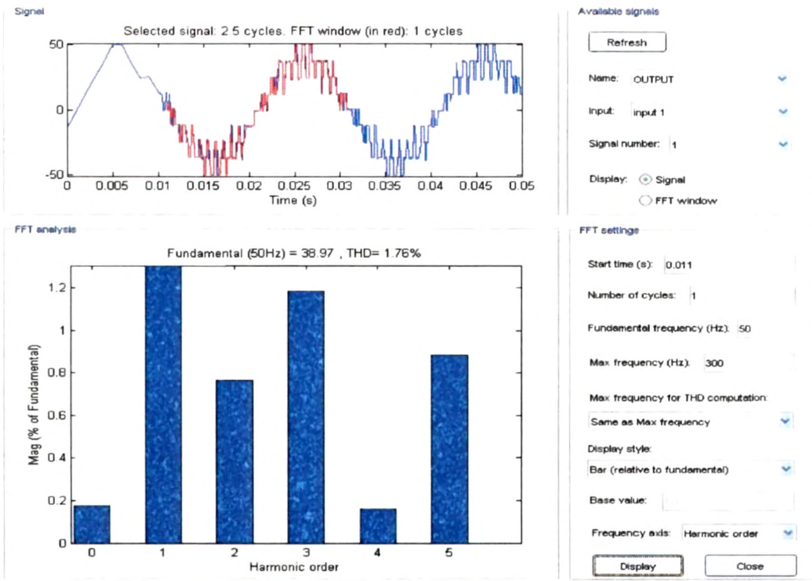
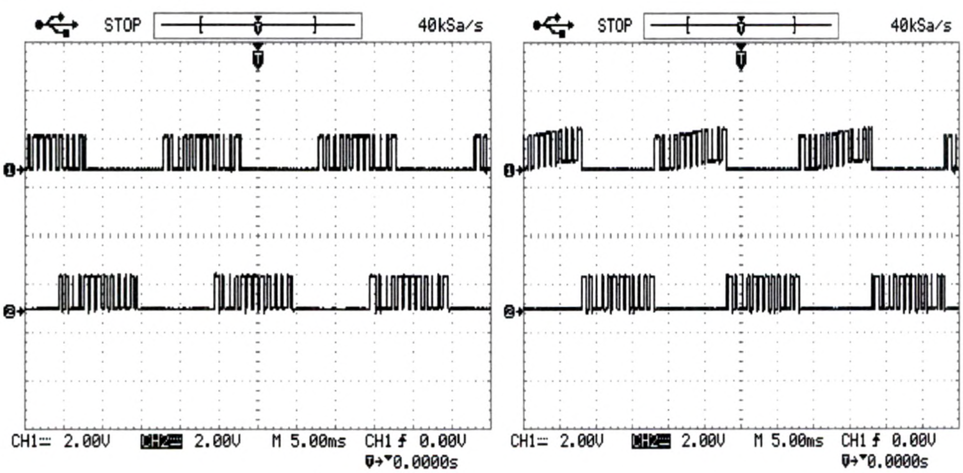


Fig. 8.26 FFT analysis and THD for 3 phase HMLI with POD modulation technique

8.2.3 HARDWARE OUTPUT FOR THREE PHASE HMLI WITH APOD MODULATION TECHNIQUE

i) BATTERIES AS SUPPLY

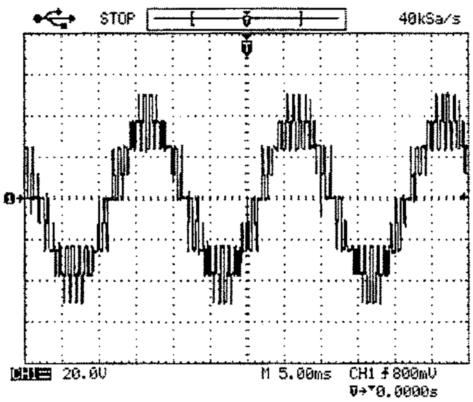
Fig 8.27(a) shows control signals with APOD modulation technique for switches which are 120^0 apart.



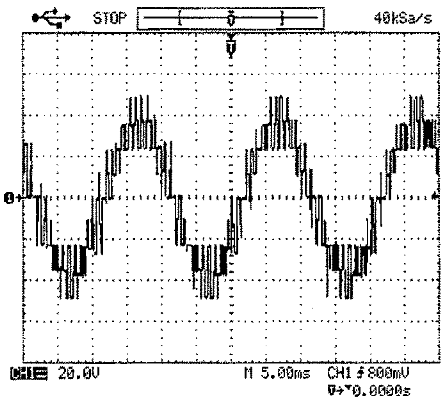
(a) G_1 G_1' **(b) G_1 G_3**

Fig. 8.27 Control signals for three phase HMLI with APOD modulation technique

Fig 8.28(a) shows 9 level line to line output voltage(v_{RY}).100 Ω- 1 W resistors are star connected as load. Fig 8.28(b) output voltage v_{YB}. Fig 8.29(a) output voltage v_{RB}

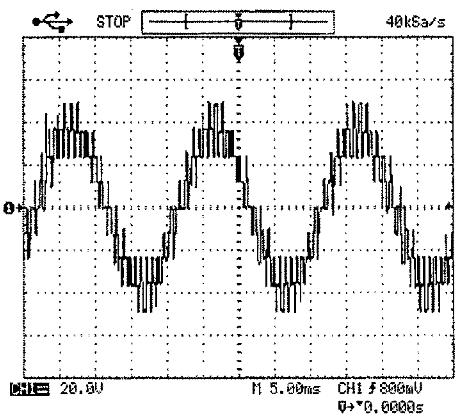


(a) v_{RY}

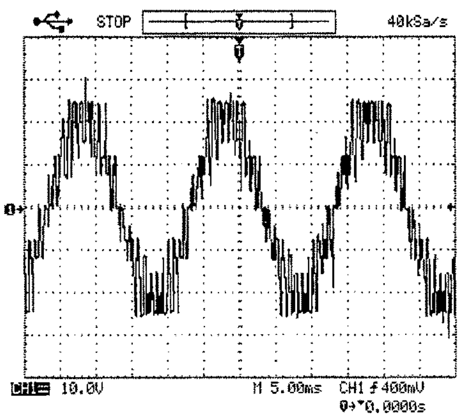


(b) v_{RB}

Fig. 8.28 Three phase HMLI output with APOD modulation technique

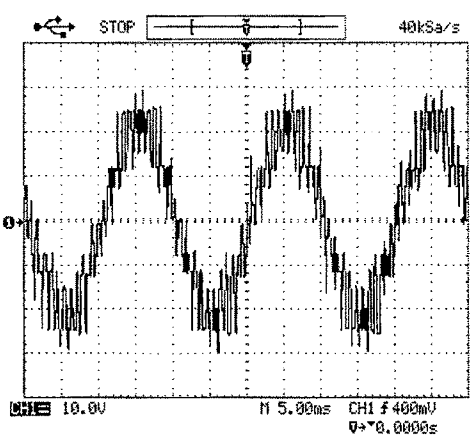


(a) v_{YB}

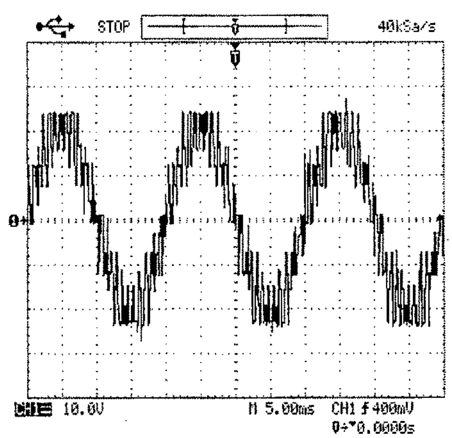


(b) v_R

Fig. 8.29 Three phase HMLI output with APOD modulation technique



(a) v_Y



(b) v_B

Fig. 8.30 Three phase HMLI output with APOD modulation technique

. Fig 8.29(b) shows 7 level v_R phase output voltage while Fig 8.30 (a) and (b) show 7 level output voltages v_Y and v_B respectively. Control signals were given at sample rate of 25 kHz due to limitation of MATLAB SIMULINK. Fig. 8.31 is THD obtained from .csv file imported to MATLAB for one output and other values are mentioned in Table 8.1.

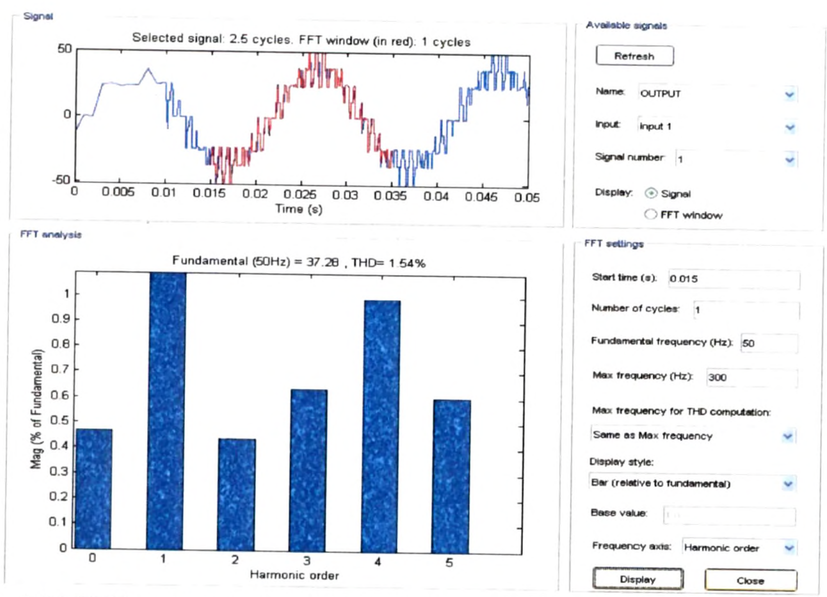
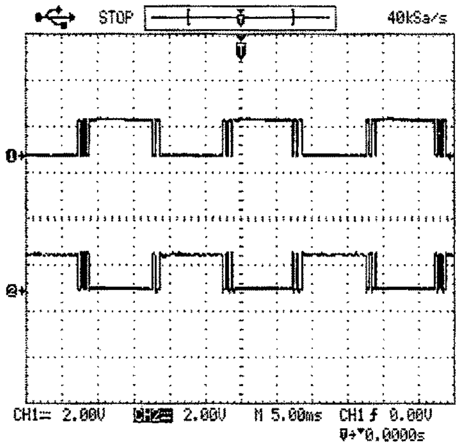


Fig. 8.31 FFT analysis and THD for 3 phase HMLI with APOD modulation technique

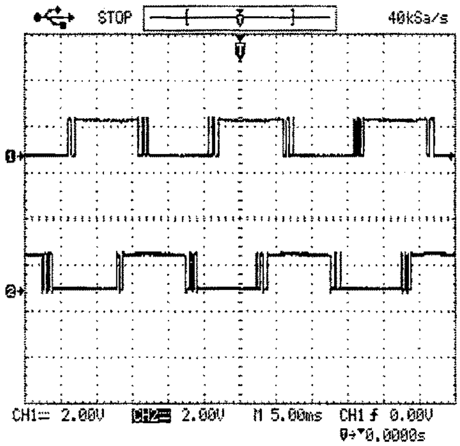
8.2.4 HARDWARE OUTPUT FOR THREE PHASE HMLI WITH THIRD HARMONIC MODULATION TECHNIQUE (PD)

i) BATTERIES AS SUPPLY

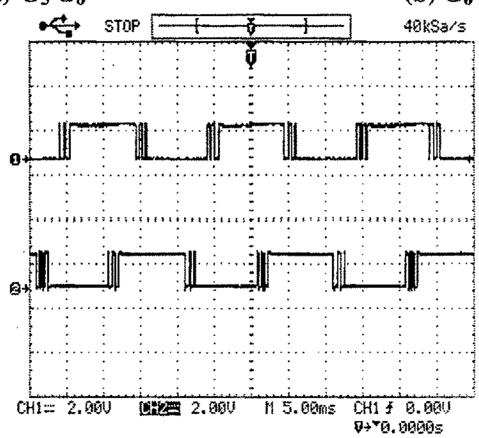
Fig 8.32(b) shows control signals with third harmonic injection modulation technique for switches which are 120^0 apart. Fig 8.33(a) shows 9 level line to line output voltage(v_{RY}). 100 Ω- 1 W resistors are star connected as load. Fig 8.33(b) shows output voltage v_{YB}. Fig 8.34(a) is output voltage v_{RB}. Fig 8.34(b) shows 7 level v_R phase output voltage while Fig 8.35(a) and (b) show 7 level output voltage v_Y and v_B respectively. Control signals were given at sample rate of 25 kHz due to limitation of MATLAB SIMULINK. Fig. 8.36 is THD obtained from .csv file imported to MATLAB for one output and other values are mentioned in Table 8.1.



(a) G_5 G_6

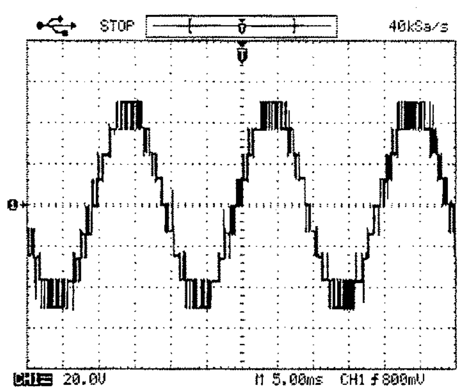


(b) G_6 G_6'

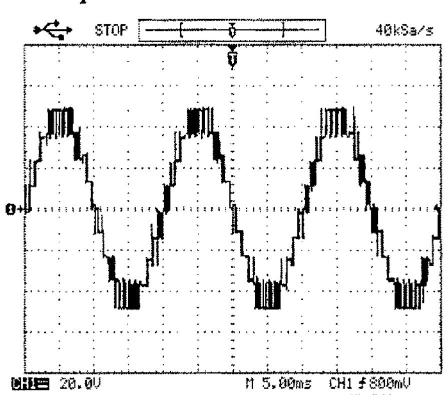


(c) G_5 G_5'

Fig. 8.32 Control signals for three phase HMLI with third harmonic injection modulation technique

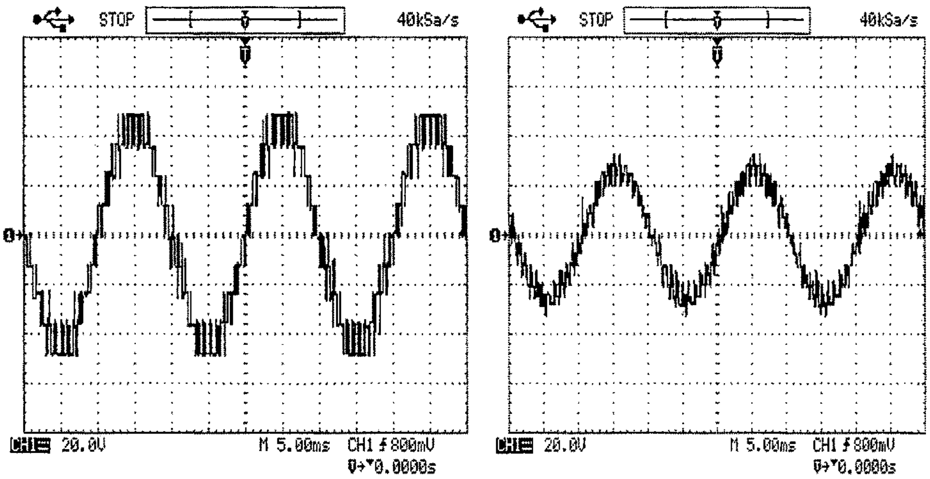


(a) v_{RY}



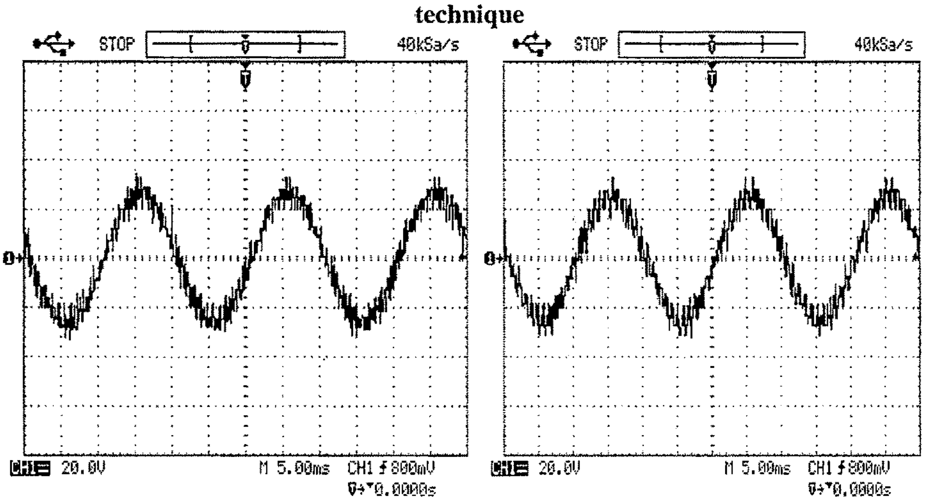
(b) v_{YB}

Fig. 8.33 Three phase HMLI output with third harmonic injection modulation technique



(a) v_{YB} (b) v_R

Fig. 8.34 Three phase HMLI output with third harmonic injection modulation technique



(a) v_Y (b) v_B

Fig. 8.35 Three phase HMLI output with third harmonic injection modulation technique

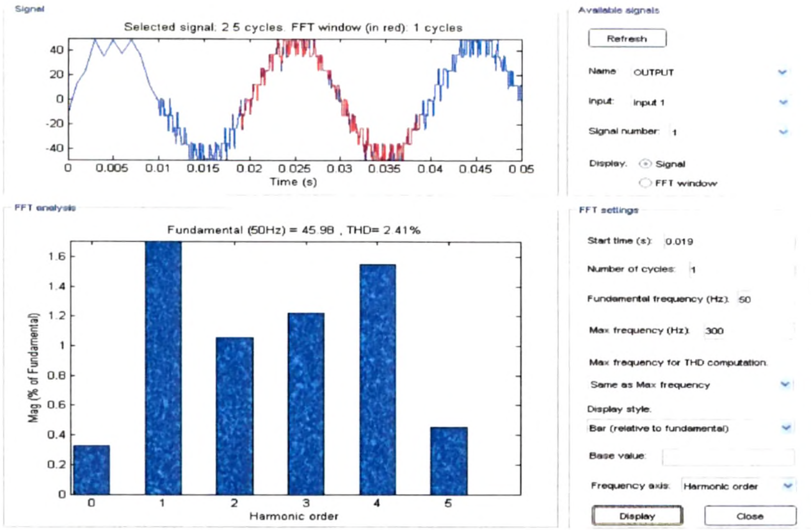
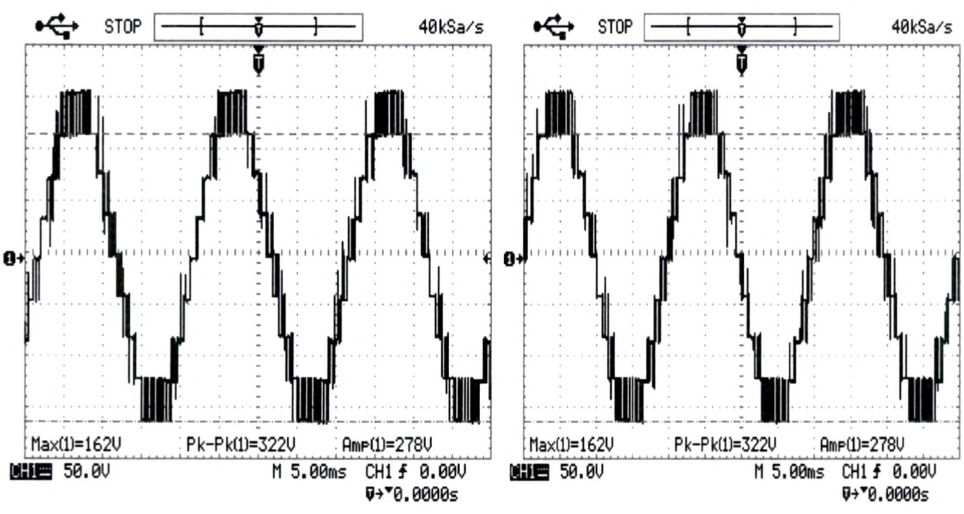


Fig. 8.36 FFT analysis and THD for 3 phase HMLI with third harmonic injection modulation technique Y-B

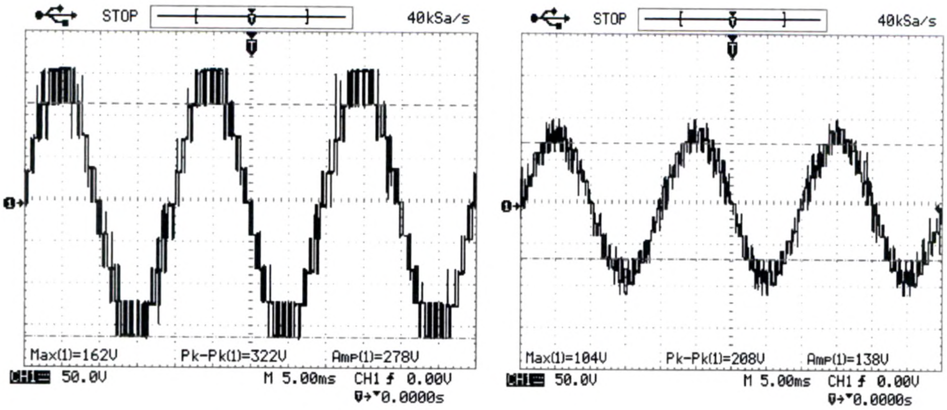
ii) REGULATED POWER SUPPLY

Fig 8.37(a) shows 9 level line to line output voltage(v_{RY}). 1 kΩ- 10 W resistors are star connected as load. Fig 8.37(b) output voltage v_{YB}. Fig 8.38(a) output voltage v_{RB}. Fig 8.38(b) shows 7 level v_R output voltage while Fig 8.39(a) and (b) show 7 level output voltage v_Y and v_B respectively. Control signals were given at sample rate of 25 kHz due to limitation of MATLAB SIMULINK. Fig. 8.40 is THD obtained from .csv file imported to MATLAB for one output and other values are mentioned in Table 8.1.



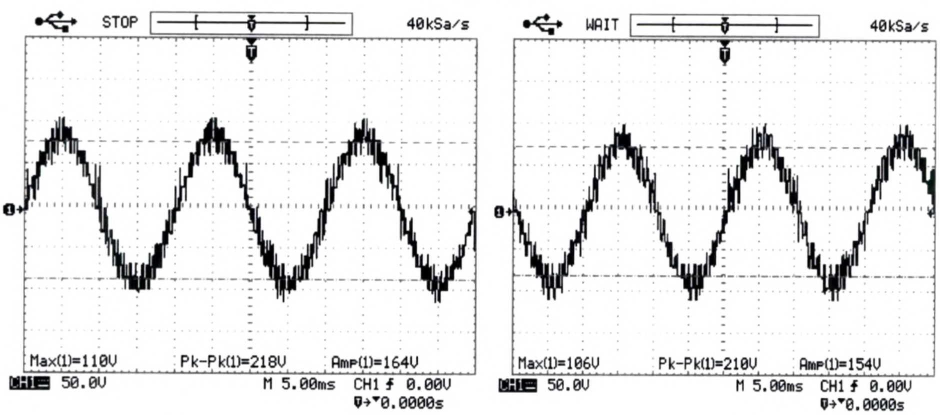
(a) v_{RY} **(b) v_{RB}**

Fig. 8.37 Three phase HMLI output with third harmonic injection modulation technique



(a) v_{YB} (b) v_R

Fig. 8.38 Three phase HMLI output with third harmonic injection modulation technique



(a) v_Y (b) v_B

Fig. 8.39 Three phase HMLI output with third harmonic injection modulation technique

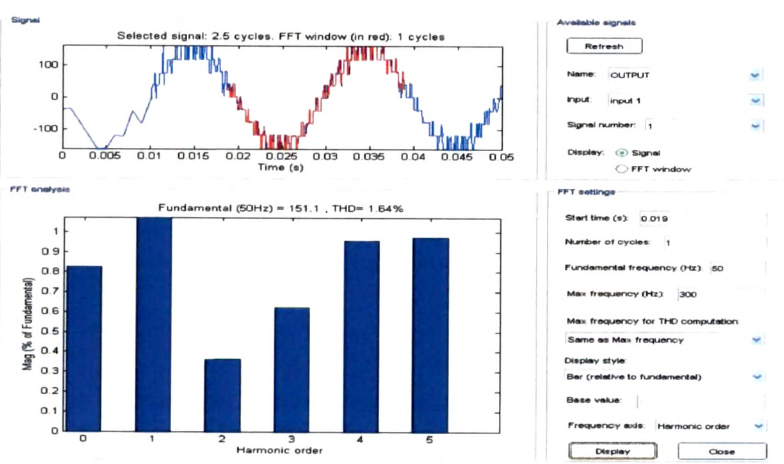


Fig. 8.40 FFT analysis and THD for 3 phase HMLI with third harmonic injection modulation technique

Table 8.1 Summary of output

Modulation Technique	Line to line voltage	DC input in Volts	Start Time	Simulation Results			Hardware Results			
				V_o	V_1	% THD	V_o	load Ω	V_1	% THD
PD	v_{RY}	24-12	.01/.011	96	41.64	0.59	90	100	37.88	1.26
	v_{YB}		.01	96	41.5	0.74	90	100	37.09	1.95
	v_{BR}		.01/.027	96	41.64	0.53	90	100	37	2.48
	v_{RY}	80-40					316	330	119.8	1.73
	v_{YB}						320	330	119.5	1.8
	v_{RY}	80-40	.02/.019	320	138.5	0.49	292	33	112	1.27
	v_{BR}		.02/.029	320	138.5	0.45	296	33	113.1	1.38
	v_{YB}		.02/.029	320	138.5	0.53	296	33	111.6	1.35
POD	v_{RY}	24-12	.01/.011	96	41.52	0.49	96	100	38.97	1.76
	v_{YB}		.012	96	41.56	0.58		100		
	v_{BR}		.017	96	41.57	0.65	96	100	38.28	1.58
APOD	v_{RY}	24-12	.015		41.57	0.19	96	100	37.28	1.54
	v_{YB}		.015/.01		41.58	0.37/.87	96	100	36.76	1.82
	v_{BR}		.01/.02		41.53	.18/.63	96	100	36.82	1.72
Third Harmonic Injection	v_{RY}	24-12	.01	96	45.86	2.14	96	100	46.57	2.44
	v_{YB}		.019	96	45.43	1.96	96	100	45.98	2.41
	v_{BR}		.015	96	45.82	2.37	96	100	46.13	2.52
	v_{RY}	80-40	.019/.02	320	152.6	1.51	322	1k	148.6	1.65
	v_{YB}		.019/.017	320	153	1.77	322	1k	150.4	2.06
	v_{BR}		.019/.019	320	152.6	1.51	322	1k	151.1	1.64
PD	v_O	12-12-12	.01	48	24	0.79	40	100	18.41	4.61

Number of cycles for THD----1

Output levels for 3 phase----9

V_1----Fundamental voltage

V_o----Peak to peak output voltage in volts

THD noted at maximum frequency as 300Hz.

vo----Single phase output

8.3 SUMMARY

In this chapter hardware results are given. Hardware was tested at low voltage battery and high voltage regulated power supply. Results were compared for low and high voltage for different modulation techniques. It is observed that there is no much difference in THD as voltage is increased from low to high.

It is observed that with PD modulation technique THD obtained from simulation much more less with respect to THD obtained from hardware results for low as well as high DC voltage applied. POD and APOD modulation techniques are implemented for low DC voltage. Variation in THD is more for APOD modulation technique when simulated and applied for hardware as compared to POD modulation technique results.

It was expected that THD would be less for third harmonic injection modulation technique as compared to other modulation techniques, but practically THD is more.