Three to Single Phase Buck-Boost Regulated High Power Quality Cycloconverter

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***Abstract*— In this paper, a new approach to design a good power quality three to single phase Cycloconverter regulated and controlled by Buck-Boost converters differentially connected across the load has been proposed. The proposed Cycloconverter improves Power Quality by reducing Total Harmonic Distortion(THD) of input line current, input Power Factor (Pf) and overall Efficiency (η) of the power conversion. Traditional twelve thyristor (SCR) cycloconverter has high THD (19% and above) and has only two quadrant operation on V~f plane. The proposed Cycloconverter has a lower THD (15% and below), requires only eight switches and it has the advantage of four quadrant control of voltage and frequency. Simulation has been performed in PSIM and Simulink for resistive and inductive loads with Back-emf. Open loop sliding Technique is applied to ensure good power quality at desired performance. Details of Operation and circuit performance is presented in this paper.**

***Index Terms*—Converters, Frequency conversion, Insulated gate bypolar transistor, Power conversion harmonics, Power Quality, Switching converters, Switched-mode power supply, Thyristor, Voltage control.**

I. Introduction

CYCLOCONVERTER is a static frequency changer (SFC) designed to convert constant voltage, constant frequency AC to variable voltage variable frequency AC without any DC link. Cycloconverter is a naturally commutated SFC capable of bidirectional power flow [1]. With the advent of thyristors of high power rating and development of microcontroller control strategies, Cycloconverters are being used in heavy industries like rolling mills [4]-[6], electric traction [7], cement tube mill drive industries above 5 MW [8]-[10], wind tunnel fan drives [11], and ship propellers [12]-[14]. Traditional Cycloconverter requires a large number of thyristors, at least 12 and usually more for good motor performance, together with a complex control circuit. Cycloconverters deliver averaged sinusoidal output waveform which results low pulsating torque in rotary loads. Their input current is distorted and its Fourier series involves harmonics which include, a) higher order harmonics [7], b) sub-harmonics [16], and c) nonstandard harmonics [2], [17].

As a result, various control strategies and modulation techniques [22] are used to minimize harmonics effect on output voltage. The conventional methods of filter [20] cannot be used to reduce harmonics in Cycloconverters. Several control strategies have been developed including cosine-wave control [2], ripple voltage integral feedback control [3], current feedback method [18],double integral control [21] etc.

In this paper, switch mode power supply (SMPS) converters are employed to control the output voltages. In each cycle of the input AC signal the voltage is made unidirectional by employing full bridge rectifier. Then, depending on the required frequency at the load, this unidirectional voltage either appears on the same side or on the opposite side of the load. To provide output voltages at opposite polarities two SMPS topology based converters (one p and one n converter) are connected across the load [23]. The proposed topology differs from the available circuits in two ways. Firstly, for three phase AC-AC conversion, SMPS topology based converters is employed instead of conventional twelve SCR Cycloconverter scheme, thereby, output voltage both higher and lower than the supply voltage is achievable by controlling the duty cycle of the SMPS converter. Secondly, in case of three phase AC supply, the P and N type converters have reduced number of switches. The reduction of switches has four advantages compared to conventional Cycloconverter topologies. Firstly, it reduces the switching losses and thereby increases the efficiency. Secondly, the proposed circuits have to deal with less number of isolation schemes. Thirdly, the number of drives is reduced and finally, the proposed topology has higher reliability as the number of switches is reduced. Moreover, open loop sliding technique is applied on our proposed circuit to ensure optimum suitable operating point. As closed loop control is avoided, no stability problem arises. The performance of the proposed topology is evaluated in terms of THD, input power factor, output voltage, output frequency and efficiency along the range of the duty cycle of the control signal.

II. Proposed Circuit Configuration & Explanation

Traditional Cycloconverter is based on the principle of two back to back three phase controlled rectifier feeding the load from two opposite sides. By Controlling the firing angle of the Silicon controlled rectifier (SCR) bridge, output voltage can be controlled. During the first half time period of the output voltage, one bridge (P-converter) is active while second bridge (N-converter) is turned off. Again, during the second half time period, N-converter is on and P-converter is turned off. Input and output characteristics of a traditional twelve SCR Cycloconverter is provided in Fig. 1.Fig. 2 shows the FFT of input line current for the input line current shown in Fig. 1.

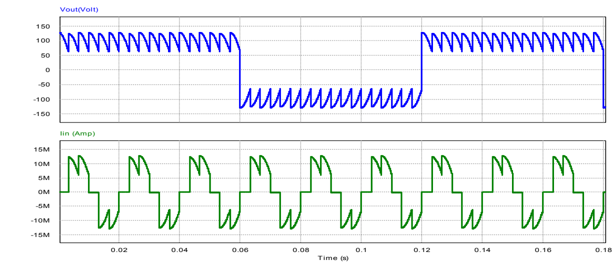

Fig. 1. Output Voltage(Volt) and Input Line Current (Amp.)

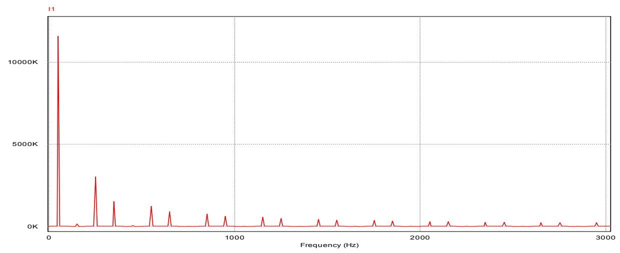

Fig. 2. FFT of input line current

Harmonics closer to fundamental frequency can not be eliminated unless large reactor filter is used. On the other hand, large filter would deteriorate input power factor and efficiency. So it is extremely difficult to ensure all the power quality parameters satisfactorily using traditional Cycloconverters without some trade-off.

In our proposed Buck-Boost Cycloconverter, input current is chopped at high frequency. As a result, harmonic frequency is far shifted from fundamental frequency. A small filter can be used for improving THD. Fig. 3 shows basic blocks of our proposed topology. We have used a bridge rectifier, input filter, an inductance of 5mH and capacitor of 7uF for Buck-Boost block, four IGBT's in total for P & N converter. For switching at high frequency, IGBT has been used for its simplicity of being voltage driven source. Two converters P-type and N-type have been used. P-type converter is active only at positive cycle of output voltage. N-type converter is active only at negative cycle of output voltage.

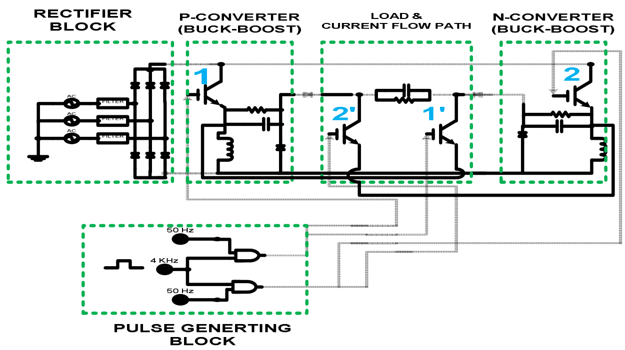

Fig. 3. Basic blocks of Buck-Boost Cycloconverter.

Firstly, three phase sine wave is rectified by a rectifier diode bridge. As a result, an unregulated DC voltage of peak sine wave magnitude is achieved at the terminals of bridge rectifier. Then this DC voltage is raised up or lowered down as per requirement by the Buck-Boost block and fed to the load from two opposite sides by P & N converter. Only one of P & N converter is active at any one period. The switching pulses for the IGBT's are shown in Fig. 4.

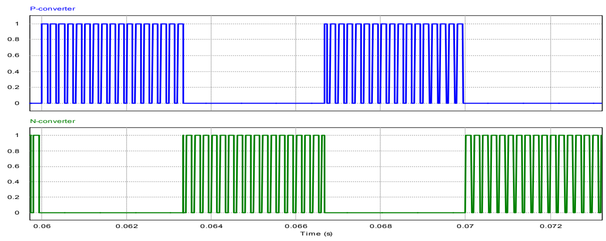

Fig. 4. Pulse Signal to Switches(IGBT)

The circuit can be explained in four modes of operation shown in Fig. 5.

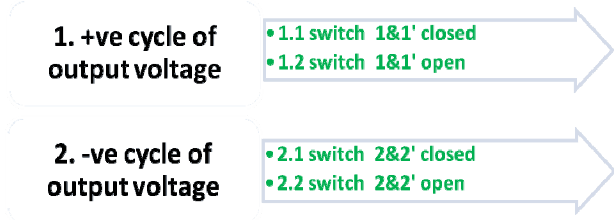

Fig. 5. Modes of operation.

At P-converter when switch 1&1' are closed, then two processes take place at the same time. Inductor of P converter energizes through Switch 1 and capacitor of P converter discharges the charge stored at previous cycle through switch 1'. Fig. 6 shows first mode of operation.

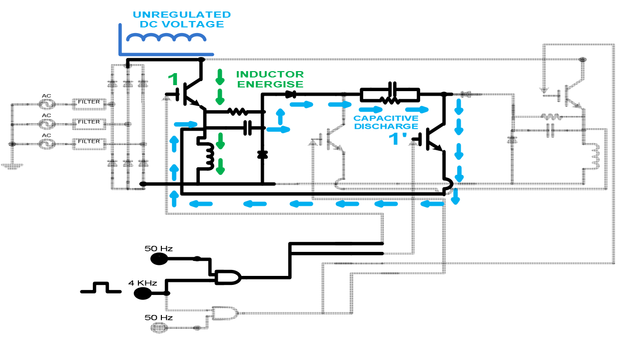

Fig. 6. Current path when switch 1&1' closed.

At P-converter when switch 1&1' are open, then two processes take place at the same time. Inductor of P-converter de-energizes through freewheeling diode and charges capacitor of P-converter. Capacitor across load discharges through load resistance. Fig. 7 shows second mode of operation.

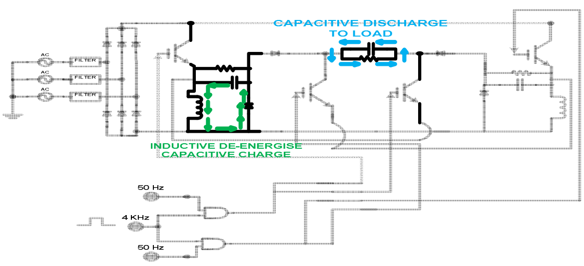

Fig. 7. Current path when switch 1&1' open.

At N-converter when switch 2&2' are closed, then two processes take place at the same time. Inductor of N-converter energizes through Switch 2 and capacitor of P-converter discharges the charge stored at previous cycle through switch 2'. Fig. 8 shows third mode of operation.

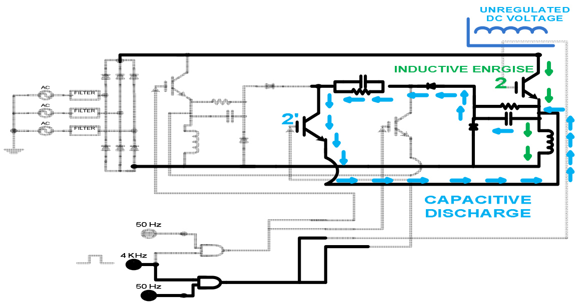

Fig. 8. Current path when switch 2&2' closed.

At N-converter when switch 2&2' are open, then two processes take place at the same time. Inductor of N-converter de-energizes through freewheeling diode and charges capacitor of N-converter. Capacitor across load discharges through load resistance. Fig. 9 shows fourth mode of operation.

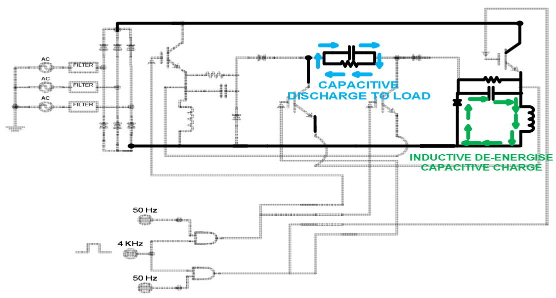

Fig. 9. Current path when switch 2&2' open.

The output voltage magnitude can be raised up or lowered down by adjusting duty cycle of the pulse given to both P & N-converter. The output frequency can be changed by adjusting the active period of both P & N-converter.

III. Simulation Results

The simulation has been performed using PSIM Professional Version 9.0.3.400, MATLAB Professional Version 7.1.0.246(R14)Service Pack 3 & SIMULINK. Fig. 10 & Fig. 11 provide PSIM & SIMULINK circuit.

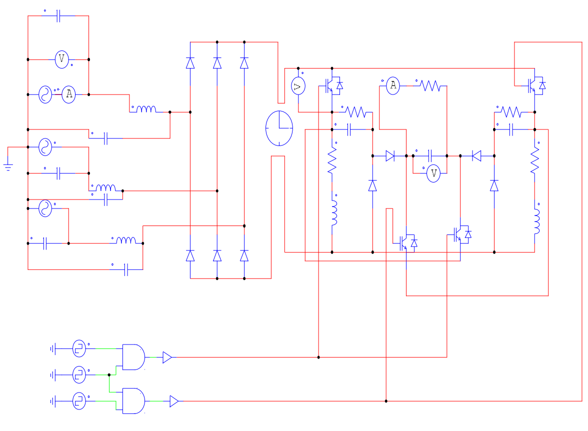

Fig. 10. PSIM circuit configuration.

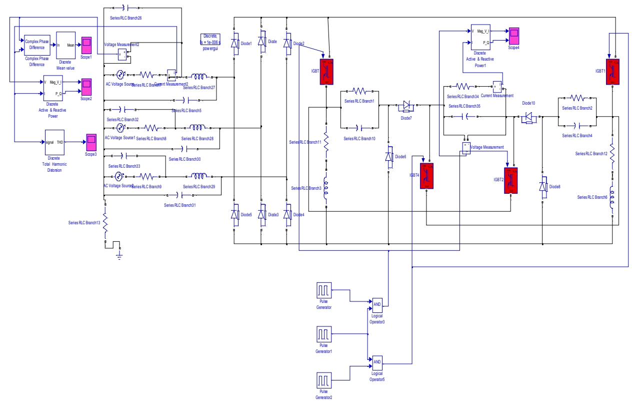

Fig. 11. SIMULINK circuit configuration.

To perform open loop sliding technique, Points of best performance in terms of power quality on the duty cycle~frequency coordinate system should be selected. Table I shows converter performance at different duty cycle at different switching frequency.

TABLE I
PERFORMANCE AT DIFFERENT SWITCHING FREQUENCY

f	D	THD %	η %	pf	I_in (max)	Vo (max)	Vo (rms)
2k	.8	10	81.3	.96	13.6	812	641.1(boost)
4k	.15	25.1	63.1	.73	.70	154.4	104.3(buck)
	.20	25.0	65.5	.90	1.15	214.0	150.5(buck)
	.25	20.0	67.5	.95	1.43	260.1	185.2(buck)
	.30	19.9	69.5	.96	1.56	269.7	196.8(buck)
	.35	19.6	71.7	.96	1.72	282.0	210.1(buck)
	.40	12.4	79.4	.97	2.92	383.5	287.1(boost)
	.50	9.81	81.6	.98	4.11	458.7	355.7(boost)
	.60	8.67	83.7	.99	6.34	568.8	450.8(boost)
	.70	6.81	84.0	.97	10.7	728.2	592.6(boost)
	.75	6.60	83.4	.94	13.0	815.5	682.9(boost)
	.80	6.62	81.0	.84	19.9	892.7	755.5(boost)
6k	.20	22.1	72.9	.78	.72	206.6	118.3(buck)
	.25	22.6	75.1	.90	.99	258.7	155.4(buck)
	.30	19.5	76.5	.95	1.41	299.2	195.5(buck)
	.35	17.4	77.6	.97	2.09	328.5	241.2(boost)
	.40	8.61	84.4	.99	3.5	437.5	290.0(boost)
	.50	7.13	84.4	.99	5.33	525.6	423.1(boost)
	.60	7.01	85	.99	7.43	639.4	526.7(boost)
	.70	6.68	84.2	.95	13.5	787.7	667.6(boost)
	.75	6.78	83.2	.88	18.0	857.6	741.6(boost)
8k	.25	27.1	79.5	.83	.921	261.3	139.6(buck)
	.30	32.7	80.6	.91	1.42	314.9	185.3(buck)
	.35	31.4	80.9	.94	2.16	360.9	238.1(boost)
	.50	11.5	86.0	.99	5.27	574.39	438.1(boost)
	.60	7.09	85.9	.98	9.76	688.56	577.7(boost)
	.70	6.81	84.4	.92	15.8	827.67	710.5(boost)
	.75	6.95	82.9	.83	20.6	883.8	767.2(boost)
10k	.20	24.9	79.1	.64	.66	204.9	103.0(buck)
	.23	28.1	80.3	.76	.96	238.4	125.2(buck)
	.25	29.9	82.2	.83	.94	262.3	141.2(buck)
	.27	31.2	81.9	.87	1.24	274.3	158.6(buck)
	.30	33.3	83.0	.90	1.39	316.6	186.3(buck)
	.50	13.9	87.2	.98	7.15	606.28	439.6(boost)
	.60	7.92	86.2	.97	11	725.38	611.6(boost)
	.70	7.25	84.3	.89	17.6	859.6	736.8(boost)
	.75	7.67	82.4	.79	22.6	899.3	776.8(boost)

Best duty cycle in terms of performance is selected separately for Boost and Buck region for the frequency band provided in the table. I. Selection Criteria for Boost region has been chosen as: PF>.9,η>75%,Vout/Vin>1.5. Under this limitation, duty cycle which provides lowest THD is selected. Selection Criteria for Buck region has been chosen as: pf>.85,η>65%,Vout/Vin<.85. Under this limitation, duty cycle which provides lowest THD is selected for open loop sliding technique to perform. Fig. 12 shows open loop sliding technique performance.

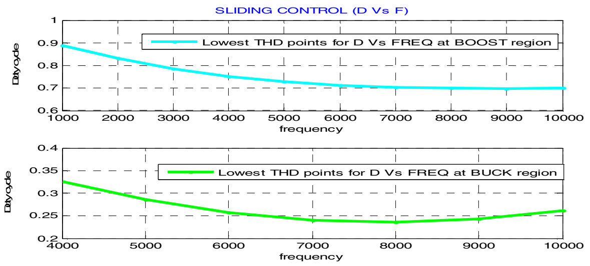

Fig. 12. Performance of Buck-Boost converter under sliding control.

Sliding technique ensures operating points for best performance of the proposed converter. The Cycloconverter performs at lowest THD at each of the points in Fig 12. Input and Output waveshapes for Buck region at sliding point of duty cycle .25 and switching frequency of 5KHz at output frequency of 16.67 Hz is shown in Fig. 13. Results obtained in PSIM and SIMULINK are provided in the same figure for comparative study.

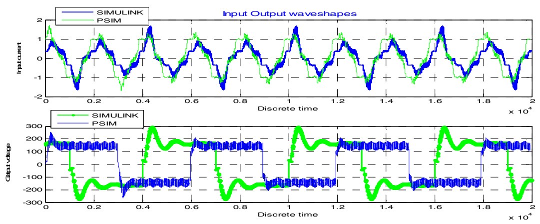

Fig. 13. Performance of Buck-Boost converter at Buck region where output frequency is reduced three times than input frequency.

Input and Output waveshapes using PSIM for Buck region at sliding point of duty cycle .25 and switching frequency of 6KHz at output frequency of 150 Hz is shown in Fig. 14.

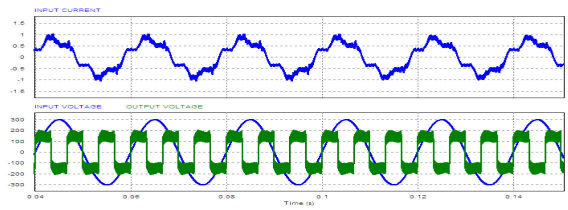

Fig. 14. Performance of Buck-Boost converter at Buck region where output frequency is increased three times than input frequency

Input and Output waveshapes for Boost region at sliding point of duty cycle .75 and switching frequency of 4KHz at output frequency of 16.67 Hz is shown in Fig. 15.

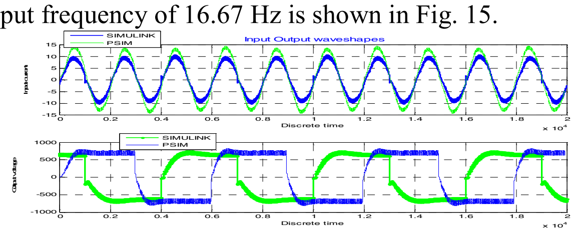

Fig. 15. Performance of Buck-Boost converter at Boost region where output frequency is reduced three times than input frequency.

Input and Output waveshapes for Boost region at sliding point of duty cycle .75 and switching frequency of 4KHz at output frequency of 150 Hz is shown in Fig. 16.

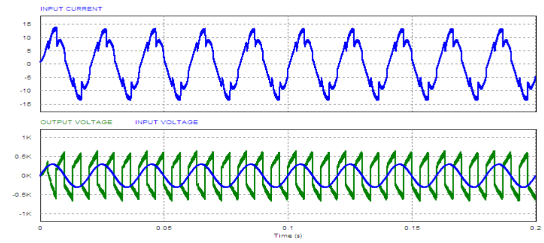

Fig. 16. Performance of Buck-Boost converter at Boost region where output frequency is increased three times than input frequency.

Fast Fourier Transform (FFT) analysis can be performed to inspect the THD performance for input current. FFT for the input current in Fig. 15 is provided in Fig. 17.

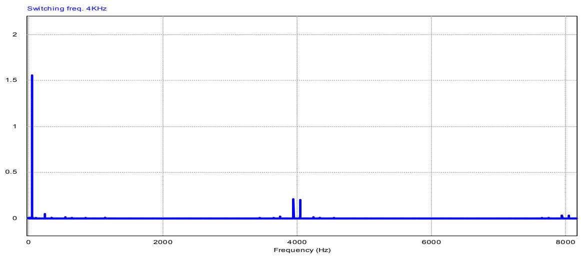

Fig. 17. FFT of input Current

IV. PERFORMANCE APPRAISAL

Power quality parameters vary with duty cycle even at a fixed switching frequency. Fig. 18 and Fig. 19 shows power quality performance both at Buck and Boost region at a typical switching frequency of 5 KHz.

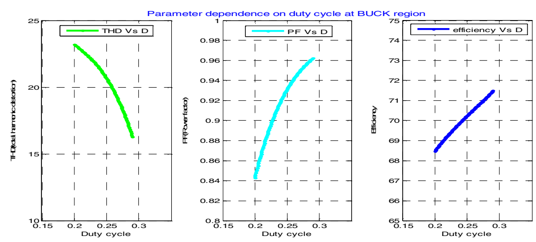

Fig. 18. Power Quality Vs Duty cycle of the converter at Buck region.

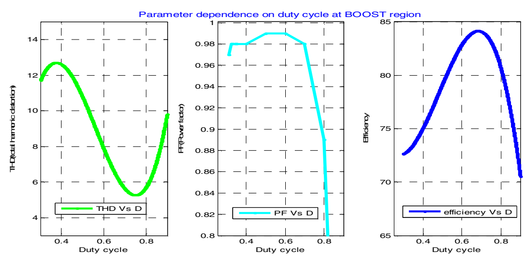

Fig. 19. Power Quality Vs Duty cycle of the converter at Boost region.

Power quality parameters also vary with switching frequency even at a fixed Duty cycle. Fig. 20 and Fig. 21 show Power Quality performance both at Buck and Boost region at duty cycle corresponding to .30 and .70.

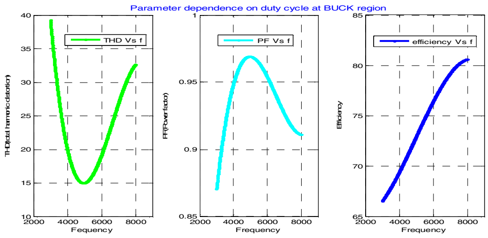

Fig. 20. Power Quality Vs Switching frequency of the converter at Buck region.

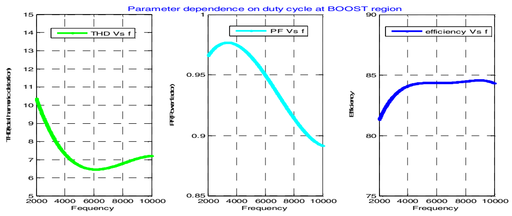

Fig. 21. Power Quality Vs Switching frequency of the converter at Boost region.

Our proposed Cycloconverter is also fully compatible to variation in load. Though the performance varies with the change in load, still the overall performance lies within the imposed power quality boundary. Table II shows the performance of the proposed converter under different load both at Buck and Boost region.

TABLE II
PERFORMANCE TRACKING OF THE CONVERTER TO LOAD VARIATION

Mode	f	D	R=50			R=150		
			THD	pf	η %	THD	pf	η %
Buck	4k	0.25	20.1	.95	62	20	.95	71.2
	5k	0.25	21.2	.93	64	21	.93	75.1
	6k	0.25	25.1	.91	66	22	.90	78.0
	7k	0.25	26.3	.91	68	22	.86	80.1
	8k	0.25	27.0	.92	69	23	.82	82.4
	9k	0.25	26.1	.92	71	24	.78	84.3
	10k	0.25	27.2	.92	72	25	.76	85.1
Boost	1k	0.90	40.1	.93	73	45	.91	80.3
	2k	0.80	10.0	.94	75	11	.96	81.5
	3k	0.80	7.01	.87	75	8.2	.92	81.5
	4k	0.75	6.22	.91	79	7.1	.95	83.5
	5k	0.75	5.81	.87	79	7.0	.93	83.5
	6k	0.70	6.78	.92	81	8.2	.96	84.4
	7k	0.70	6.99	.90	81	8.4	.95	84.4
	8k	0.70	7.12	.88	81	8.3	.94	84.2
	9k	0.70	7.31	.85	81	8.5	.93	84.3
	10k	0.70	7.72	.83	81	8.6	.92	84.1

Simulation has been performed in both PSIM and SIMULINK. Table III shows power quality performance obtained separately for the same circuit parameters for sliding points.

TABLE III
COMPARISON OF PSIM (P) & SIMULINK(S) RESULTS FOR SLIDING POINTS

f	D	THD (%)		pf		η(%)	
		P	S	P	S	P	S
4k	0.75	6.61	7.5	0.94	0.96	70.8	82.1
5k	0.75	6.07	6.5	0.91	0.95	81.3	85.2
6k	0.70	6.68	6.8	0.95	0.96	81.3	88.1
7k	0.70	6.84	6.3	0.93	0.95	83.4	86.4
8k	0.70	6.80	6.1	0.92	0.95	83.6	87.2
9k	0.70	6.91	5.9	0.90	0.91	84.2	84.3
10k	0.70	7.25	9.2	0.89	0.83	84.5	82.3

Proposed circuit has also been tested for purely inductive load with back emf. Table IV shows the performance at frequency of 5000Hz.

TABLE IV
PERFORMANCE AT INDUCTIVE LOAD WITH BACK-EMF(R=50, L=0.4H,E=90%)

D	pf	THD	η%	I_in(max)	Vo_max	Vo(rms)
0.12	0.82	21.0	75.3	0.760	249.6	196.3
0.14	0.90	19.4	75.3	0.981	299.0	235.9
0.16	0.94	17.3	74.6	1.26	352.7	276.5
0.18	0.97	11.3	74.5	1.51	400.1	314.4
0.20	0.98	7.69	75.2	1.56	417.5	324.2
0.30	0.99	7.67	75.5	1.90	470.4	370.7
0.40	0.99	7.41	76.3	2.44	533.4	421.9
0.50	0.99	6.86	76.5	3.22	618.3	490.2
0.60	0.98	6.28	77.4	4.60	743.1	589.9
0.70	0.96	4.80	78.5	7.84	922.1	727.1
0.80	0.81	8.10	78.9	14.5	1150	882.8

So power quality changes with the change in duty cycle even for inductive load. Fig. 22 and Fig. 23 shows dependence of power quality at Buck and Boost region for inductive load.

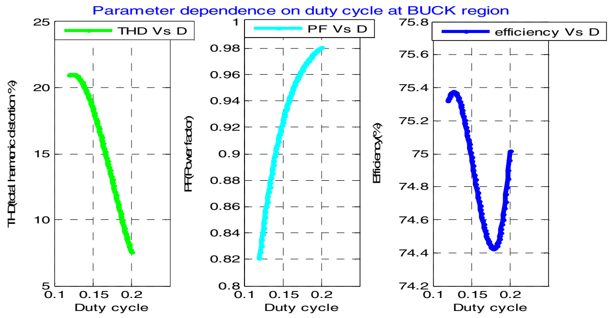

Fig. 22. Power Quality Vs Duty cycle at Buck region for motor load.

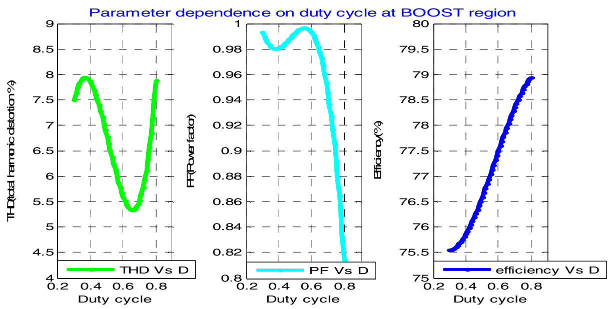

Fig. 23. Power Quality Vs Duty cycle at Boost region for motor load.

With inductive load large spike during changeover of output voltage occurs. This problem can be encountered using augmented technique [25] of voltage stability.Fig. 24 shows actual input and output waveshapes. Fig 25 shows output voltage after using augmented technique for duty cycle of .7.

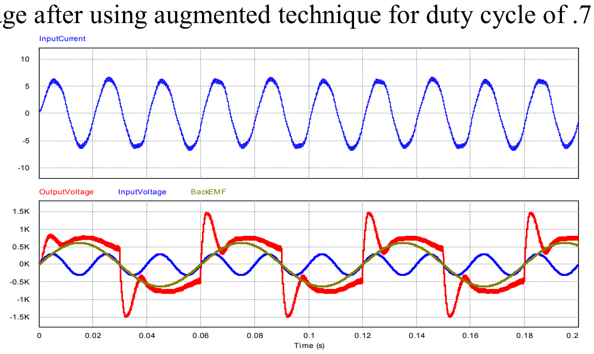

Fig. 24. Output voltage spike

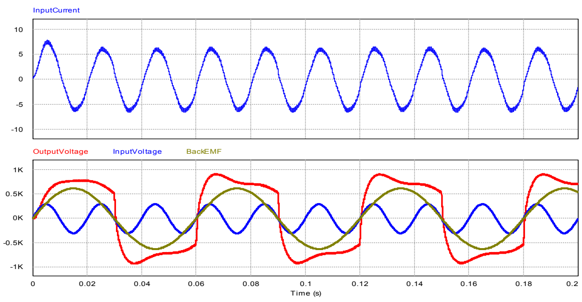

Fig. 25. Output voltage (using Augmented Technique)

Fig. 24 shows voltage spikes during changeover of output volatge due to abrupt current change through inductive load has been successfully encountered using augmented technique.

V. PRACTICAL RESULTS

Proposed circuit has been implemented practically. Input current has been observed to check reliability of the simulation results. For pulse generation Atmega 8 microcontroller has been used providing variable frequency and duty cycle. Input current without input filter is provided in Fig. 26. Fig. 27 shows low THD input current after filtering at frequency 8KHZ and D=.8.

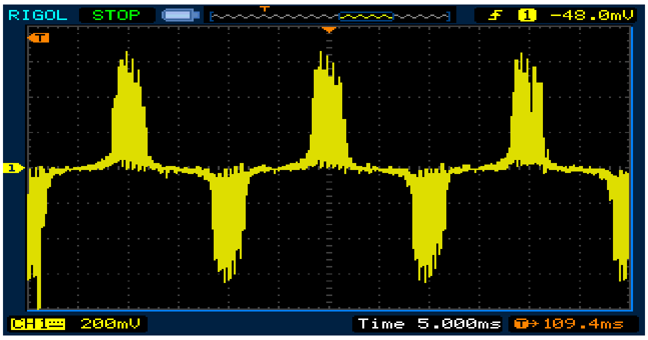

Fig. 26. Practical input current(without Filtering)

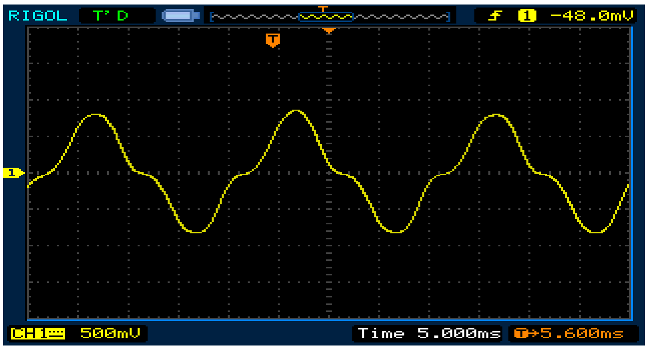

Fig. 27. Practical low THD input current(after Filtering)

VI. CONCLUSION

Three phase Cycloconverter based on Buck-Boost topology offers flexible control over voltage and frequency with reduced number of switches. Most importantly, input THD and power factor can be improved effectively with improved efficiency using small high pass filter parameters. Further research can be carried out to reduce switching loss, di/dt and dv/dt effects of IGBT's at high frequency to increase efficiency and reliability of the system.

VII. REFERENCES

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