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An Input Current Waveshaping AC-DC Converter for Rectifier Loads

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ABSTRACT

This paper presents the design and analysis of a new input AC current waveshaping AC-DC converter for cost effective harmonic mitigation under varying loads. The proposed converter consists of a delta-polygon connected autotransformer based twelve-pulse AC-DC converter and a small rating passive shunt filter tuned at 11th harmonic frequency. The proposed AC-DC converter eliminates the most dominant 5th, 7th and 11th harmonics and reduces higher order harmonics; thereby, resulting in an improved power quality at AC mains. Moreover, the design of the autotransformer is modified to make it suitable for retrofit applications, where presently a 6-pulse diode bridge rectifier is used. To validate the proposed approach, various power quality indices are presented under varying loads. Experimental results obtained on the developed converter are given to validate the model and design of the proposed converter.

Keywords: multipulse AC-DC converter, power quality improvement, delta-polygon autotransformer, passive filter

1. Introduction

There has been a substantial increase in the number of equipment making use of some kind of power processors for achieving improved performance in terms of high level power quality, energy conservation, etc. This is possibly due to the ease in availability of low cost and high rating solid state devices[1]. These power processors find applications in various industries such as electrochemical, petrochemical, large rating power supplies, adjustable speed AC motor drives, mining, etc. It is seen that the non-linear nature of these switching devices, such as diodes, used in these power processors cause harmonic current injection into the AC mains; thereby, polluting the power quality at the point of common coupling (PCC). This in turn affects the nearby consumers, causing mal-operation of sensitive electronic equipment. The drawbacks of injection of harmonics in the AC-DC converters have already gained much attention in literature[2]. Moreover, an IEEE 519 Standard[3] has been established to impose strict restrictions on both utility and consumers. This has resulted in an impetus to research in various power quality improvement techniques.

Power quality improvement may be achieved using active or passive waveshaping techniques. The active waveshapers make use of fast digital processors for controlling the switching of semi-conductor devices[4]. It results in high switching losses at high switching frequencies. Moreover, the rating of these active waveshapers is also quite high. On the other hand, passive

waveshaping techniques making use of either passive filters or multipulse converters are simple, robust, rugged and more efficient. The use of passive filters alone results in a large rating of components (typically reported rating is up to 63%)[5]. The use of twelve-pulse AC-DC converters is also a simple technique for harmonic mitigation. The use of isolated multipulse AC-DC converter configurations result in a magnetics rating of the order of 1.03 Po, where Po is the active power drawn by the converter. However, in applications where isolation is not required, the use of non-isolated converter configurations results in substantial reduction in the rating of magnetics. It has been reported that the power quality indices in a twelve-pulse AC-DC converter are not within the IEEE standard limits[7]. The use of a higher number of pulses results in improvement in power quality indices, but at the cost of increased complexity as well as cost[8-12]. To improve the THD of an AC mains current further, a 28-step current shaper has been proposed[13], but even with this configuration, the THD of an AC mains current at full load is 6.54%, which deteriorates at load variation and it is also not within the IEEE Standard 519 limits[3].

In this work, a new type of input current waveshaping AC-DC converter consisting of a delta-polygon connected autotransformer based twelve-pulse AC-DC converter along with a small rating passive shunt filter is designed and developed for power quality improvement at the AC mains[14]. The autotransformer is connected in the form of a delta-polygon, which is a combination of delta and polygon connections. This configuration results in substantial reduction in a rating of magnetics. A set of tabulated results giving the comparison of different power quality indices such as total harmonic distortion (THD) and crest factor (CF) of an AC mains current, power factor (PF), displacement power factor (DPF), distortion factor (DF), THD of supply voltage at PCC and ripple factor (RF) at DC bus is presented for a load fed from an existing 6-pulse AC-DC converter shown in Fig. 1 (referred to as Topology 'A'), 12-pulse AC-DC converter (referred to as Topology 'B') and proposed waveshaping 12-pulse AC-DC converter (referred to as Topology 'C').

A laboratory prototype of the proposed waveshaping autotransformer based 12-pulse AC-DC converter is developed and test results are presented to validate the proposed design and developed model of the proposed waveshaping converter system.
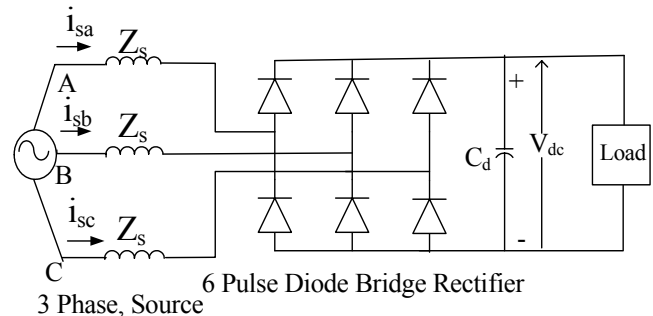

Fig. 1   Six-pulse diode bridge ac-dc converter fed load (Topology 'A')

2. Design of the Proposed Twelve-Pulse AC-DC Converter

The detailed design and analysis of the proposed 12-pulse AC-DC converter is carried out for varying loads. The complete circuit consists of an autotransformer, small rating passive shunt tuned filter and a varying load.

2.1 Design of Autotransformer for Proposed Twelve-Pulse AC-DC Converter

The minimum phase shift required for proper harmonic elimination is given by[6]:

Phase shift = 60^0/ Number of six-pulse converters

For achieving a 12-pulse AC-DC conversion, the phase shift between the two sets of voltages should be of $\pm15^0$ with respect to the supply voltages. From the supply voltages, two sets of 3-phase voltages (phase shifted through $+15^0$ and -15^0) are produced. The number of turns required for $+15^0$ and -15^0 phase shift is calculated as follows: Fig. 2a shows the winding connection of the proposed autotransformer. Fig.2b shows the corresponding phasor diagram of different phase voltages. Consider phase 'a' voltages in Fig.2a

$$V_a' = V_a + K_1 V_{ca} - K_2 V_{bc} \tag{1}$$

$$V_a'' = V_a - K_1 V_{ab} + K_2 V_{bc} \tag{2}$$

Considering the following set of voltages:

$$V_a = V\angle 0^0,\ V_b = V\angle -120^0,\ V_c = V\angle 120^0 \tag{3}$$

$$V_a' = V\angle 15^0,\quad V_b' = V\angle -105^0,\quad V_c' = V\angle 135^0, \tag{4}$$

$$V_a'' = V \angle -15^0, \quad V_b'' = V \angle -135^0, \ V_c'' = V \angle 105^0 \quad (5)$$

where V is the RMS value of phase voltage.

Using the above equations K_1 and K_2 can be calculated. These equations result in $K_1 = 0.0227$ and $K_2 = 0.138$ for the desired phase shift in an autotransformer.
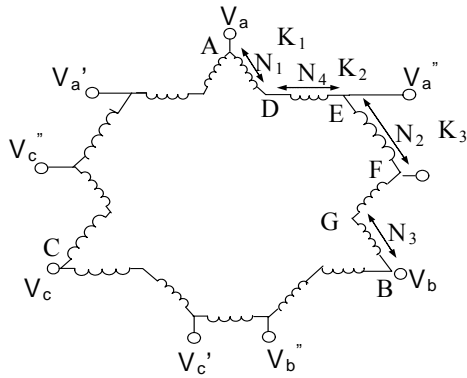

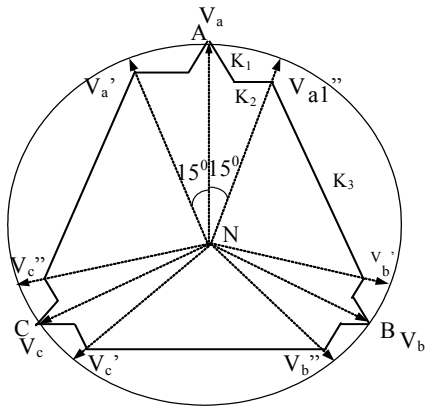Fig. 2a   Proposed autotransformer winding connection

Fig. 2b   Phasor diagram of different phase voltages in proposed
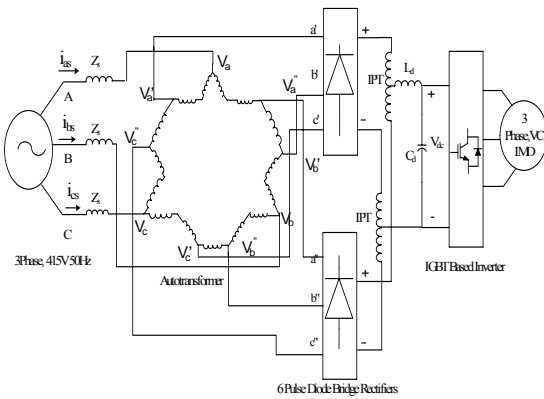autotransformer connection   based converter

Fig. 3   Proposed autotransformer based 12-pulse converter (with
phase shift of +15^0 and -15^0) fed VCIMD (Topology B)

A phase shifted voltage (e.g. V_a') is obtained by tapping a portion (0.0227) of line voltage V_{ca} and connecting one end of approximately 0.138 of line voltage (e.g. V_{bc}) to this tap. Thus the autotransformer can be designed with these known values of winding constants, i.e.: K_1, K_2 and K_3. The above designed 12-pulse AC-DC converter is referred to as Topology 'B', shown in Fig.3.

With this autotransformer arrangement, the DC link voltage obtained is slightly higher than that of a 6-pulse diode bridge rectifier output voltage. To make the proposed AC-DC converter suitable for retrofit applications, the transformer design has been modified to make its DC link voltage the same as that of a 6-pulse diode bridge rectifier. Fig.4 shows the generalized phasor diagram for achieving different voltage ratios from the autotransformer by simply varying the tapping positions on the windings. The different tap positions for retrofit arrangement have been shown on the inner circle. This ensures that both the output voltages still have the required phase shift of $\pm 15^0$ (for achieving the twelve-pulse operation). By following the above procedure, for the same DC link voltage as that of a 6-pulse diode bridge rectifier, the values of K_1', K_2' and K_3' are $K_1' = 0.042066$, $K_2' = 0.12838$ and $K_3' = 0.78746$ where K_1', K_2' and K_3' are the new constants. Fig.5 shows the schematic diagram of the proposed modified 12-pulse AC-DC converter, referred to as Topology 'C'.
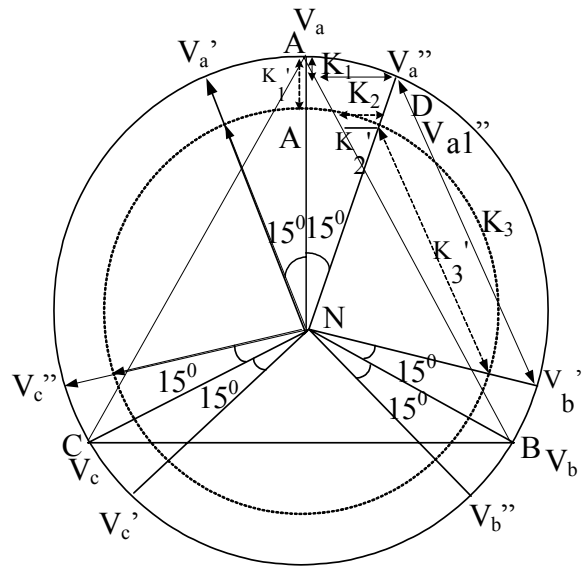

Fig. 4   Phasor diagram of voltages in the proposed autotransformer
connection   alongwith   modifications for retrofit arrangement
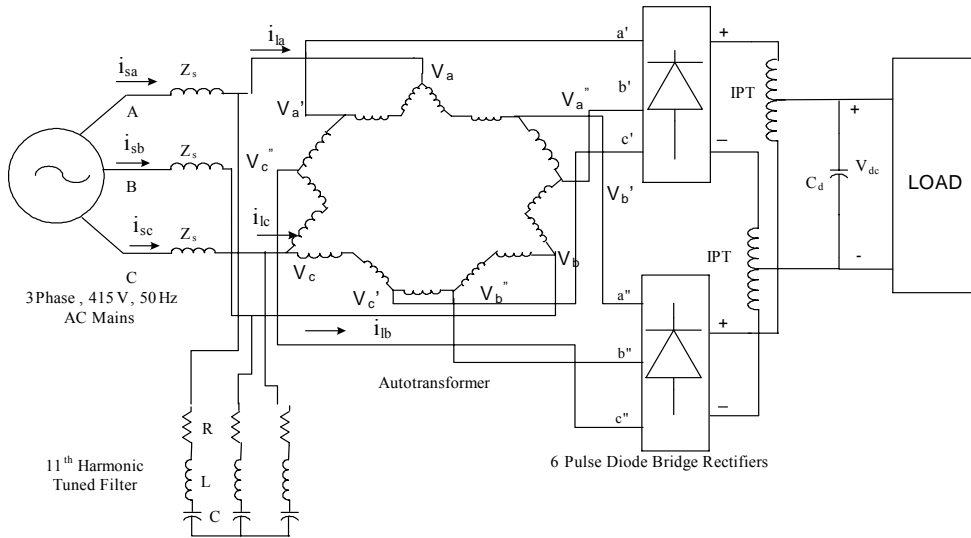
Fig. 5   Proposed ac-dc converter (Topology C)

The kVA rating of the transformer is calculated as[6]

$$kVA = 0.5\sum V_{winding} \quad I_{winding} \qquad (8)$$

The kVA rating of the interphase transformer is also calculated using the above relationship.

2.2 Design of Passive Tuned Filter

The passive shunt filter has been designed in accordance with IEEE Standard 1531-2003[15]. The design of the passive shunt filter is elucidated here.

The passive filter is designed using design equations given below[15-16]. The addition of a small rating passive shunt filter not only improves the THD of an AC mains current, but it also provides limited required reactive power to improve the fundamental power factor (DPF) of the proposed converter to unity.

The impedance of the filter branch is given as:

$$Z = R + j \ (\omega L - 1/\omega C) \qquad (9)$$

At resonance the imaginary part becomes zero. Thus resonance frequency becomes :

$$f_n = 1/ \ \{2\pi \ (LC)^{1/2}\} \qquad (10)$$

For n^{th} harmonic (11th), the inductor and capacitor impedances are $X_{ln} = n\omega \ L$ and $X_{cn} = 1/ \ (n\omega C)$. At resonance

$$X_{ln} = X_{cn}$$

The quality of the filter is a measure of the sharpness of tuning and is quantified through quality factor Q. It is defined as:

$$Q = X_{ln} \ / \ R = X_{cn} \ / \ R \qquad (11)$$

where X_{ln} is the reactance of inductor and X_{cn} is the reactance of capacitor at the resonant frequency. Here, Q is taken as 30.

3. MATLAB Based Simulation

The complete system consisting of the proposed autotransformer based AC-DC converter is simulated in a MATLAB environment along with Simulink and Power System Blockset (PSB) toolboxes. The detailed parameters of the proposed system are given in the Appendix. The source impedance has been kept at a practical value of 3% in all the simulations. The load is varied on the proposed AC-DC converter to study its effect on various power quality indices.

4. Experimentation

To validate the simulation model experimentally, a prototype of proposed autotransformer based 12-pulse AC-DC converter as shown in Fig.5 is developed in the

Table 1 Comparison of power quality parameters of a load fed from different converters

Sr. No.	Topology	THD of V_s (%) Full Load	I_s (A)		THD of I_s (%)		Distortion Factor		Displacement Factor		Power factor		DC Link Voltage			
			Full Load	Light Load (20%)	Full Load	Light Load (20%)	Full Load	Light Load (20%)	Full Load	Light Load (20%)	Full Load	Light Load (20%)	Average (V)		Ripple Factor (%)	
													Full Load	Light Load (20%)	Full Load	Light Load (20%)
1.	A	5..35	10.9	3.38	34.3	71.78	.946	0.81	.969	.970	.917	.788	302	309	.243	.179
2.	B	4.66	10.9	2.95	7.34	14.39	.997	.989	.979	.989	.976	.979	309	317	.013	.02
3.	C	2.09	10.7	2.92	3.20	6.90	.999	.994	.985	1.00	.980	.994	303	317	.045	.005

laboratory. The passive filter consisting of capacitors and a set of newly designed inductors is also developed to realize the 11th harmonic passive shunt filter. Three single-phase autotransformers have been designed and developed. Similarly, the interphase transformers (IPT's) of small ratings have been designed and fabricated. The design details of the autotransformers are: Flux density= 0.8 Tesla, Current density= 2.3A/mm^2, Core Size= 8 No. The area of cross section of core = 3225mm^2 (50.8mm x 63.5mm), E-Laminations: Length =184.1mm, width = 171.4mm, I-lamination: Length = 171.4mm, width = 50.8mm. The number of turns of different windings (shown in Fig.2a) and the conductor cross section of autotransformer are given as: N_1 = 24 (SWG = 13), N_2 = 79 (SWG = 13), N_3 = 548 (SWG = 21).

Various tests on the proposed AC-DC converter are conducted at a 3-phase line voltage of 230V, 50Hz, AC input and with varying resistive loads. The recording of the results have been carried out using Fluke make power analyzer model 43B.

5. Results and Discussion

To compare the performance of the proposed 12-pulse AC-DC converter with the existing 6-pulse AC-DC converter, a varying load is fed from the 6-pulse, 12-pulse and the proposed AC-DC converters.

5.1 Simulation Results

Fig.6 shows the supply current waveform along with its harmonic spectrum at full load for a 6-pulse AC-DC converter, showing THD of the AC mains current as 34.3%.

The THD of the AC mains current deteriorates to 71.78% at light load, as shown in Table 1. Moreover, the power factor at full load is 0.917, which deteriorates to 0.788, (as shown in Table 1) as the load is reduced. These power quality indices are not within IEEE 519 Standard[3] limits. The performance of the 12-pulse AC-DC converter (Topology 'B') is shown in Figs.7-8. The THD of the AC mains current at full load is 7.34% as shown in Fig.7 and that under a light load is 14.39%, as shown in Fig.8. These parameters are also not within IEEE 519 Standard limits[3].

The observed performance of the proposed waveshaping AC-DC converter is shown in Fig.9, showing the waveforms of supply voltage (v_s), supply current (i_s) and DC link voltage (V_{dc}). It is seen that the supply voltage and current are in phase with each other, demonstrating the unity power factor operation. The waveform of supply current at full load along with its harmonic spectrum is shown in Fig.10, showing the THD as 3.20% at full load. At light load, the performance is shown in Fig.11, showing the THD of the AC mains current as 6.90%.
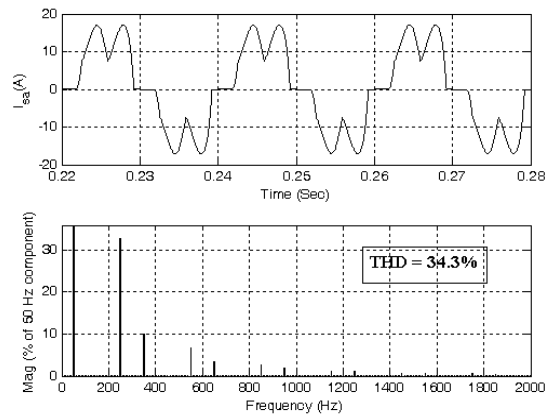

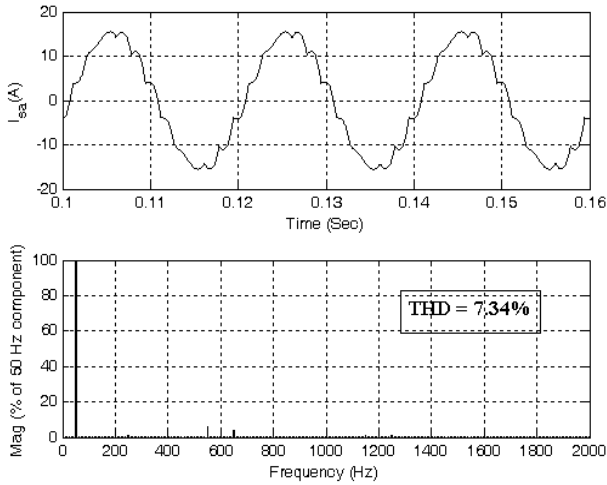Fig. 6　Supply current and its harmonic spectrum at full load in Topology 'A'

Fig. 7   Supply current and its harmonic spectrum at full load in Topology 'B'

5.2 Experimental Results

Various tests have been conducted on the developed prototype of the proposed waveshaping converter. Fig. 12 shows the waveforms of supply voltage (v_{ab}) and supply current (i_{sc}) along with the harmonic spectrum of the supply current at full load. It shows the THD of the AC mains current as 3.7%. This supply current is slightly distorted due to a presence of harmonics and the THD of the supply current is observed to be 3.7%. Similarly, Fig.13 shows these waveforms at light load, showing the THD of the AC mains current as 7.9%. The effect of load variation on the proposed 12-pulse AC-DC converter is shown in Table 2. It can be observed from Table 2 that the power factor is mostly

Fig. 8   Supply current and its harmonic spectrum at light load in Topology 'B'
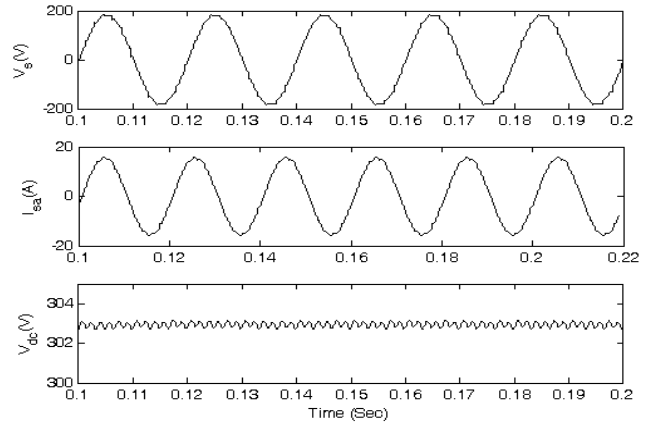

Fig. 9   Waveforms of supply voltage, supply current and dc link voltage in Topology 'C'
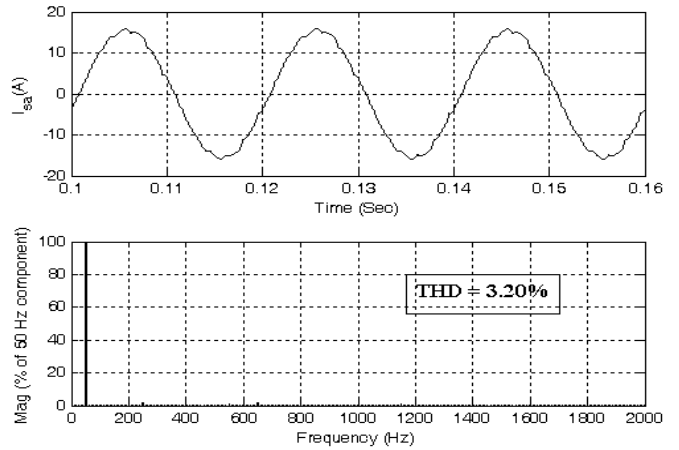

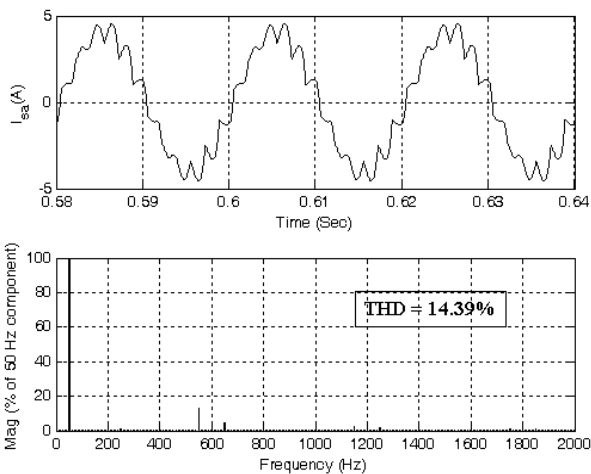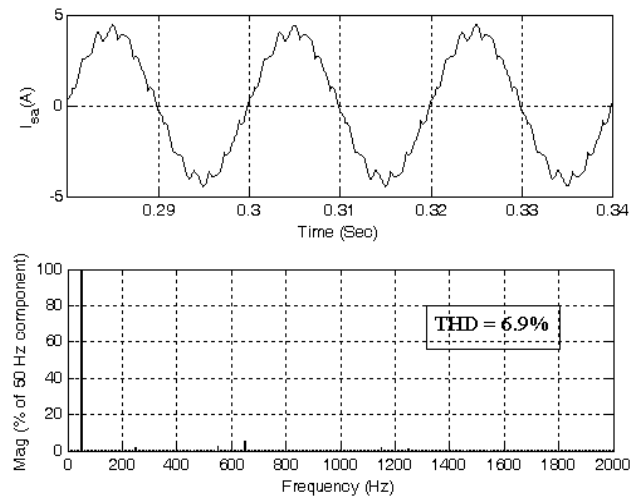Fig. 10   Supply current and its harmonic spectrum at full load in Topology 'C'

Fig. 11   Supply current and its harmonic spectrum at light load in Topology 'C'

near unity in the wide operating range and the THD of the AC mains current is always less than 8%. This is within the IEEE Standard 519 limits[13] for SCR>20.

The passive shunt tuned filter has been designed such that the drawn AC mains current does not increase with the addition of the harmonic filter. Table 2 shows the variation of supply current (i_{sa}) and converter input current (i_{la}) with a load on the rectifier. It can be observed that the supply current (i_{sa}) is mostly less than the converter input current (i_{la}). This clearly shows the effectiveness of the proposed waveshaping converter.

Table 2   Experimental Comparison of power quality indices under varying loads in proposed 12-pulse ac-dc converter

AC Mains Current I_{sa} (A)	Converter Current I_{la} (A)	THD (%)		CF of I_s	DF	DPF	PF	V_{dc} (V)
		I_s	V_s					
2.75	2.76	7.9	1.2	1.4	.997	0.97	0.967	317
4.60	4.64	6.0	1.2	1.4	.998	1.00	0.998	315
5.58	5.64	5.3	1.1	1.4	.998	1.00	0.998	313
7.65	7.83	4.5	1.1	1.4	.998	1.00	0.998	310
9.31	9.40	4.1	1.1	1.4	.999	1.00	0.999	306
11.28	11.52	3.7	1.0	1.4	.999	1.00	0.999	303

Fig. 12   Recorded waveforms of supply voltage (v_{ab}) and current waveforms (i_{sc}) and harmonic spectrum of supply current at full load in proposed 12-pulse ac-dc converter system
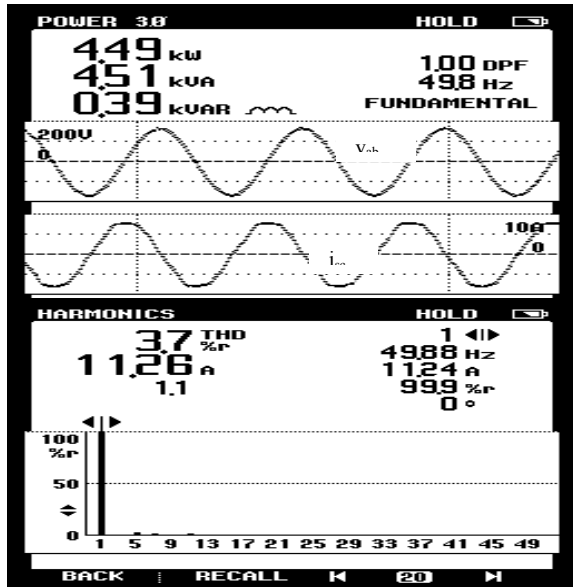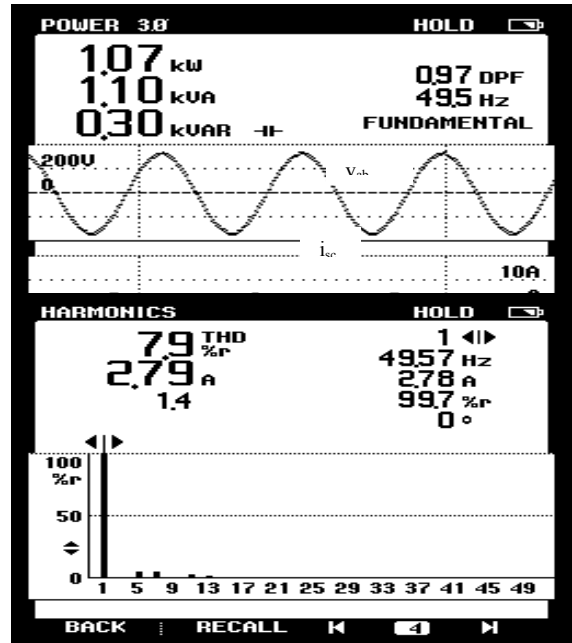

Fig. 13   Recorded waveforms of supply voltage (v_{ab}) and current waveforms (i_{sc}) and harmonic spectrum of supply current at light load in proposed 12-pulse ac-dc converter system

It is also observed that the RMS current drawn from the three-phase AC mains has decreased reasonably as compared to that in a 6-pulse AC-DC converter at varying load condition. Moreover, there is an improvement in the DC link voltage parameters. The ripple in the DC link voltage has decreased sharply, indicating the need of a lower rating capacitor filter for maintaining the same ripple factor, resulting in a further savings of capital cost.

On the magnetics front, there is also a reduction in rating, as it needs an autotransformer of 0.93kVA, an interphase transformer of 0.29kVA and a passive filter of 0.36kVA, totaling to 1.58kVA, which results in its rating of only 33% of the load power rating. It further results in saving in space, volume, size and cost of the power processing unit.

6. Conclusions

A new input current waveshaping AC-DC converter feeding varying load has been designed, simulated and developed to demonstrate its improved performance. The proposed AC-DC converter has resulted in the THD of supply current less than 8% in a wide operating range of

the load with a near unity power factor operation. The proposed converter has resulted in a reduction in rating of the magnetics, leading to the saving of weight, size, volume and overall cost of the converter system.

Appendix

System Parameters:

Rated Power =5kW, Supply voltage =230V, 3-Phase, 50Hz.

Magnetics Rating:

Autotransformer rating = 0.93kVA, Interphase transformer rating = 0.29kVA, Passive Filter = 0.36kVA.

Passive filter components: R = 0.5 ohm, L = 4mH, C = 20μF.

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