A New Waveshaper for Harmonic Mitigation in Vector Controlled Induction Motor Drives

Bhim Singh*, Vipin Garg†, and G. Bhuvaneshwari*

Abstract – This paper deals with a new waveshaping technique for cost effective harmonic mitigation in ac-dc converter feeding Vector Controlled Induction Motor Drives (VCIMD's) for improving power quality at the point of common coupling (PCC). The proposed harmonic mitigator consists of a polygon connected autotransformer based twelve-pulse ac-dc converter and a small rating passive shunt filter tuned for 11^{th} harmonic frequency. This ac-dc converter eliminates the most dominant 5^{th}, 7^{th}, and 11^{th} harmonics and imposes the reduction of other higher order harmonics from the ac main current, thereby improving the power quality at ac mains. The design of autotransformer is carried out for the proposed ac-dc converter to make it suitable for retrofit applications, where presently a 6-pulse ac-dc converter is used. The effect of load variation on VCIMD is also studied to demonstrate the effectiveness of the proposed ac-dc converter in a wide operating range of the drive. Experimental results obtained on the developed laboratory prototype of the proposed harmonic mitigator are used to validate the model and design of the ac-dc converter.

Keywords: Autotransformer, Multipulse AC-DC Converter, Passive Filter, Power Quality, VCIMD

1. Introduction

The increased use of vector controlled induction motor drives (VCIMD's) in various applications such as electrochemical and petrochemical applications, textile mills, waste water treatment plants, air conditioning, etc. has highlighted the problem of harmonic pollution [1-3]. This is mainly due to the fact that these drives generally use a three-phase diode bridge for rectification, which results in the injection of harmonics into ac mains, thereby polluting the power quality at the point of common coupling (PCC). This has further led to the publication and enforcement of various power quality standards such as IEEE Standard 519 [4], IEC 61000-3-2 [5], etc.

Different waveshaping techniques have been reported in the published literature [4-14]. Active shunt, series, and even hybrid filters provide satisfactory performance [6], but they are expensive and questionable in reliability, apart from large switching losses incurred at high switching frequencies.

The passive waveshaping techniques have retained their popularity since their inception. The use of passive filters is very popular in the industry these days, as they are rugged and reliable. But, to meet the requirement of various power quality standards such as IEEE 519 [4], the rating of passive filters is very high [7]. Moreover, under light load condition, their performance deteriorates. The use of multipulse ac-dc converters is another equally important waveshaping technique [8]. A large number of autotransformer based solutions have been proposed throughout the literature [8-12]. It is seen that a twelve-pulse converter is simplest (regarding construction and operation), but the power quality indices are not within IEEE standard limits. As the pulse number increases, the performance of the converter improves, but at the cost of increased complexity as well as cost.

This paper presents a new waveshaping technique using a polygon connected autotransformer based twelve-pulse ac-dc converter along with a small rating passive shunt filter. This scheme is able to provide the power quality indices within limits as per the standards [4-5]. It is observed that the proposed harmonic mitigator performs well even during load variation on the drive. A set of tabulated results giving the comparison of different power quality parameters such as total harmonic distortion (THD) and crest factor (CF) of the ac mains current, power factor (PF), displacement factor (DPF), distortion factor (DF), THD of supply voltage at PCC, and ripple factor (RF) at the DC bus is presented for a VCIMD fed from an existing 6-pulse ac-dc converter, (as shown in Fig. 1, referred to as Topology 'A'), 12-pulse ac-dc converter (as shown in Fig. 2, referred to as Topology 'B') and proposed harmonic mitigator (as shown in Fig. 3, referred to as Topology 'C'). The laboratory prototype of the proposed autotransformer based twelve-pulse ac-dc converter is developed and test results are presented to validate the proposed design and developed model of the harmonic mitigation system.

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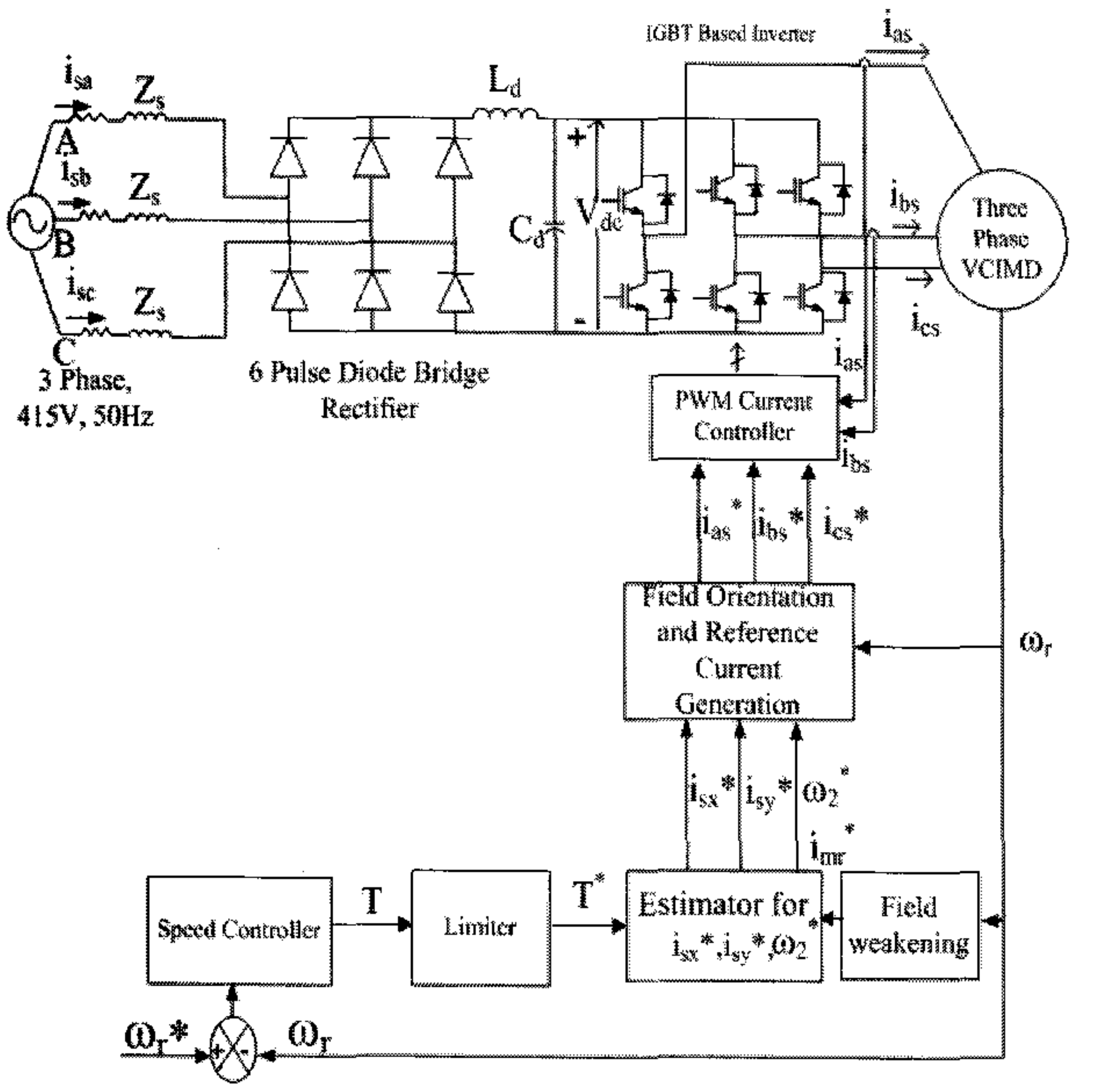

Fig. 1. Six-pulse diode bridge rectifier fed vector controlled induction motor drive. (Topology A)

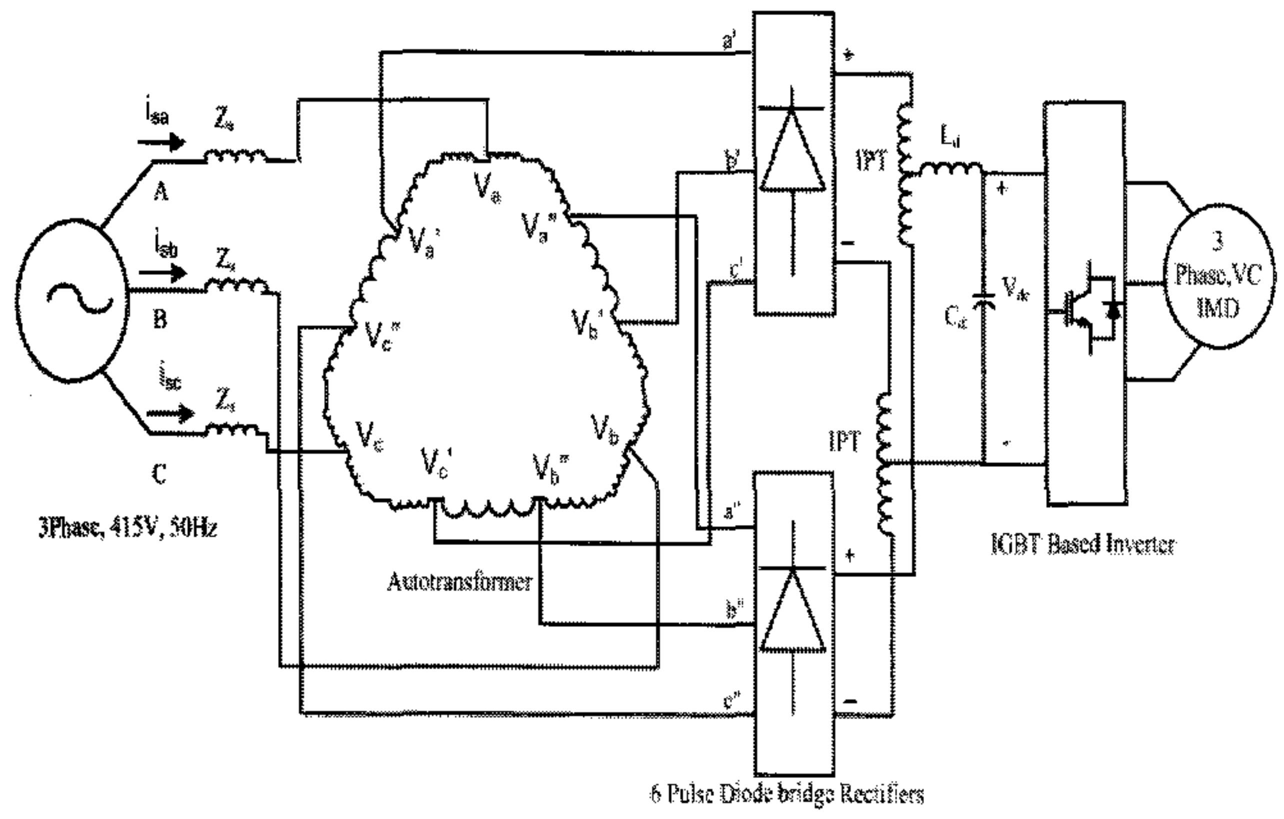

Fig. 2. Polygon autotransformer based 12-pulse converter fed VCIMD. (Topology B)

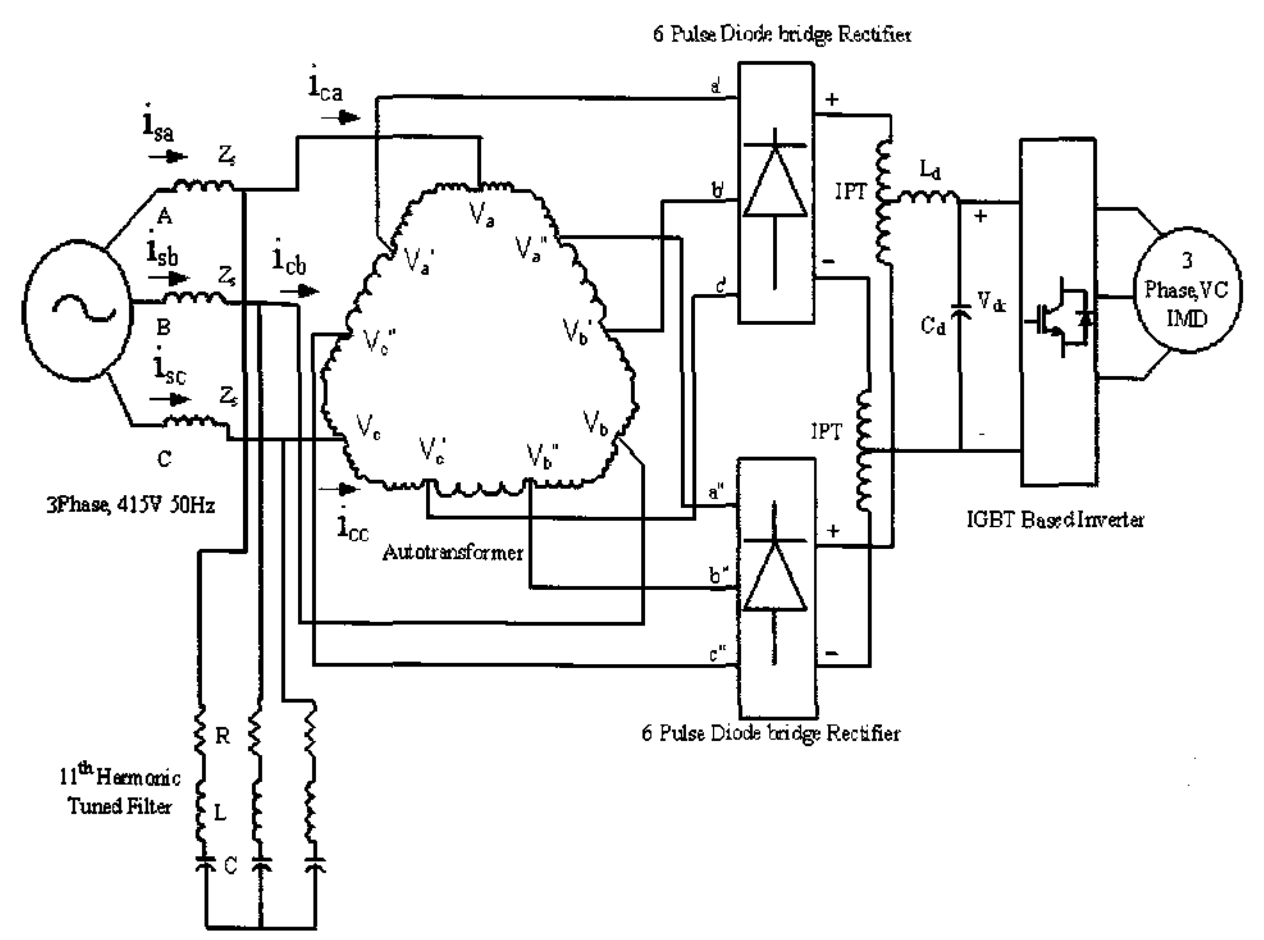

Fig. 3. Proposed ac-dc converter fed VCIMD. (Topology C)

2. Analysis and Design of Proposed Harmonic Mitigator

The proposed ac-dc converter feeding a VCIMD is presented in Fig. 3. The complete circuit is divided into three parts, namely, autotransformer, passive filter, and VCIMD. The design details of different parts of the proposed converter are given here.

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

The fundamental concept of harmonic elimination through autotransformers makes use of two or more converters, where the harmonics generated by one converter are cancelled by the other converter through proper phase shift given by [8]:

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

For achieving 12-pulse ac-dc conversion, the phase shift between the two sets of voltages may be either 0^0, 30^0, and $\pm 15^0$ with respect to the supply voltages. In this work, 12-pulse rectification is achieved based on $\pm 15^0$ to reduce the size of the magnetics.

The detailed design procedure for the proposed 12-pulse ac-dc converter is given here, which has flexibility in varying the transformer output voltages for making them suitable for retrofit applications, by simply changing the tap positions.

To achieve 12-pulse rectification, the necessary requirement is the generation of two sets of line voltages of equal magnitude which are 30^0 out of phase with respect to each other (either $\pm 15^0$, 0^0, and 30^0). 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 shifts are calculated as follows. Consider phase 'A' voltages in Fig. 4a as:

$$V_a' = V_a + K_1 V_{ca} - K_2 V_{bc} \quad (1)$$

$$V_a'' = V_a - K_1 V_{ab} + K_2 V_{bc} \quad (2)$$

Assume the following set of voltages:

$$V_a = V\angle 0^0,\ V_b = V\angle -120^0,\ V_c = V\angle 120^0,\ V_{ab} = 1.732V\angle 30^0,\ V_{bc} = 1.732V\angle 90^0,\ V_{ca} = 1.732V\angle -30^0 \quad (3)$$

Similarly,

$$V_a' = V\angle +15^0,\quad V_b' = V\angle -105^0,\quad V_c' = V\angle 135^0 \quad (4)$$

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

where V is the rms value of phase voltage.

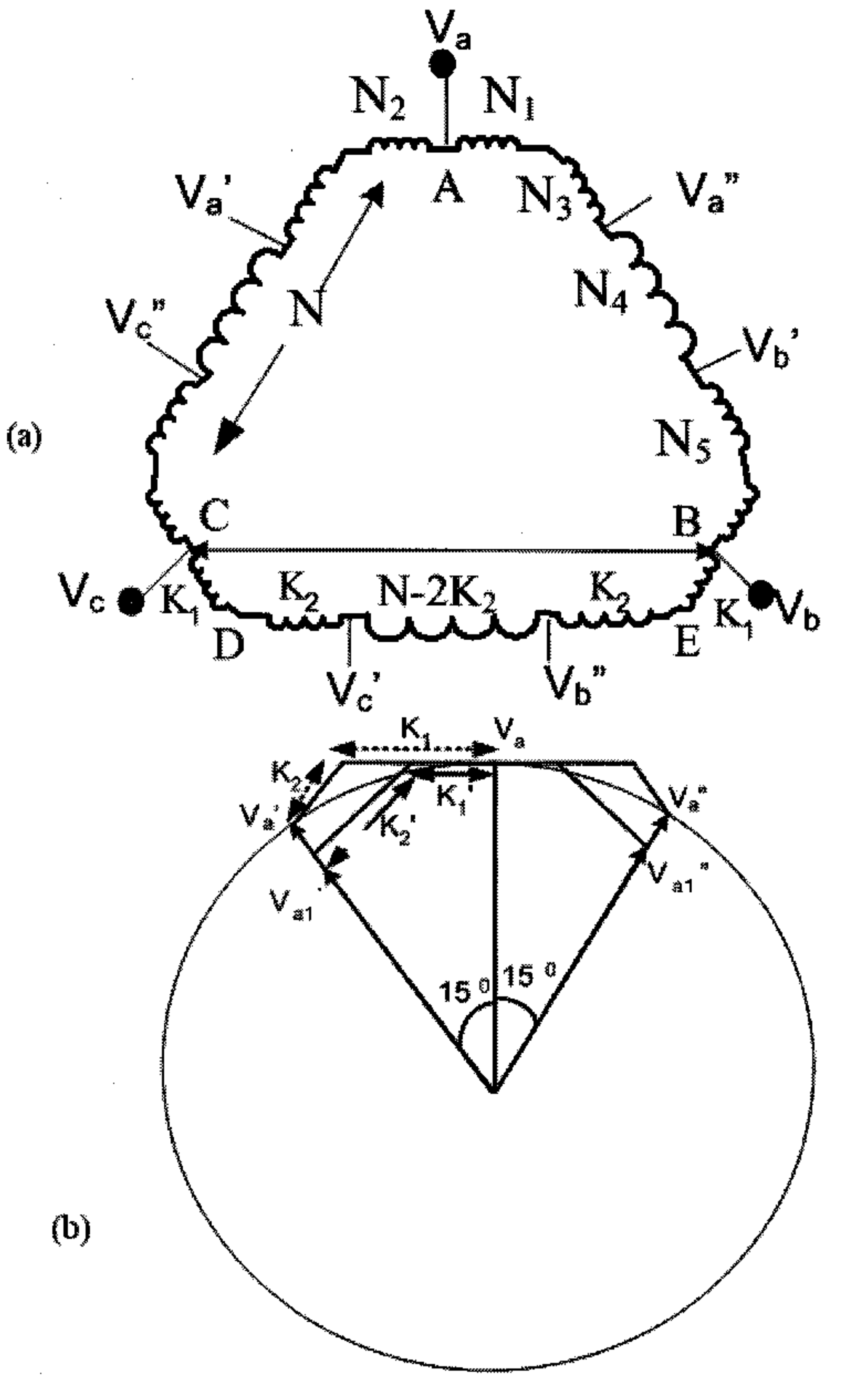

Fig. 4. Proposed autotransformer (a) winding connection diagram (b) vector diagram of phasor voltages for 12-pulse based proposed harmonic mitigator for retrofit applications.

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

The angle between CB and CD in Fig. 4a is 60^0, similarly, the angle between BC and BE is 60^0. Thus, from the parallelogram CBED in Fig. 4a, it can be written as:

$$K_1 \cos 60^0 + K_2 + (N-2K_2) + K_2 + K_1 \cos 60^0 = 1 \quad (6)$$

$$K_1 + N = 1, \text{ giving } N = 0.862 \quad (7)$$

A phase shifted voltage (e.g. V_a') is obtained by tapping a portion (0.138) of line voltage V_{bc} and connecting one end of a portion (0.0227) of line voltage (e.g. V_{ca}) to this tap.

The phasor diagram revealed in Fig. 4b represents the generalized diagram showing the relationship among various phase voltages for achieving variable magnitude transformer output voltages, which are phase shifted through $\pm 15^0$ (for achieving the 12-pulse operation). The values of K_1 and K_2 are varied to get the same dc link voltage as that of a 6-pulse ac-dc converter while ensuring an angle of $\pm 15^0$ between the two sets of voltages. For retrofit arrangement, the constants are $K_1' = 0.1268$, $N = 0.8732$, and $K_2' = 0.04$. Thus, by simply changing the transformer winding tapping, the same dc link voltage as that of the 6-pulse ac-dc converter is obtained.

The kVA rating of the autotransformer and interphase transformer is calculated as [8]:

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

2.2 Design of Passive Shunt Tuned Filter

The passive shunt filter has been designed in accordance with IEEE Standard 1531-2003 [13]. The design of the passive shunt filter is elucidated here.

1) Design Equations:

The passive filter is designed using the design equations given below [13-14]. The addition of a small rating passive filter not only improves the THD of the ac mains current, it also provides limited reactive power to the system.

The impedance of the filter branch is given as:

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

where C is the capacitance of the filter capacitor. At resonance the imaginary part becomes zero. Thus resonance frequency becomes:

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

For n^{th} harmonic (11^{th}), 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:

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

Where X_{ln} is reactance of the inductor and X_{cn} is reactance of the capacitor at the resonant frequency. In this work, Q is considered as 30.

2) Filter Design Constraints:

There are various issues in the design of a passive shunt filter for its proper functioning in harmonic reduction. The key issues are mentioned here:

a) Minimizing harmonic source current

The prime objective of the filter design is to minimize the harmonic currents in the ac mains. This is ensured by minimizing the filter impedance at the harmonic frequencies so that the harmonic filter acts as a sink for the harmonic currents.

b) Minimizing fundamental current in passive filter

To ensure that the installation of passive filter does not cause system loading, the fundamental current in the passive filter is minimized by maximizing the passive filter impedance at the fundamental frequency.

c) Environment and ageing effect

The capacitors with metallized film construction lose capacitance as they age. Similarly, the manufacturer tolerance of the harmonic filter reactor may result in tuned frequency higher than that recommended. IEEE Standard 1531[13] recommends that the passive filters are tuned at 6% below the rated frequency so that it will exhibit acceptable tuning at the end of its 20 year life. Here, the passive filter has been tuned at 517Hz for the 11^{th} harmonic corresponding to the 50 Hz fundamental frequency.

3. MATLAB Based Model

The proposed ac-dc converter feeding VCIMD is simulated in a MATLAB environment along with Simulink and Power System Blockset (PSB) toolboxes. Fig. 5 shows the MATLAB model of the proposed harmonic mitigator feeding VCIMD to improve various power quality indices and Fig. 6 shows the MATLAB model of a 10 hp VCIMD. The detailed parameters of the induction motor are given in Appendix A. The 10 hp induction motor is controlled using indirect vector control technique. The detailed control equations of the vector controlled induction motor are provided in Appendix B.

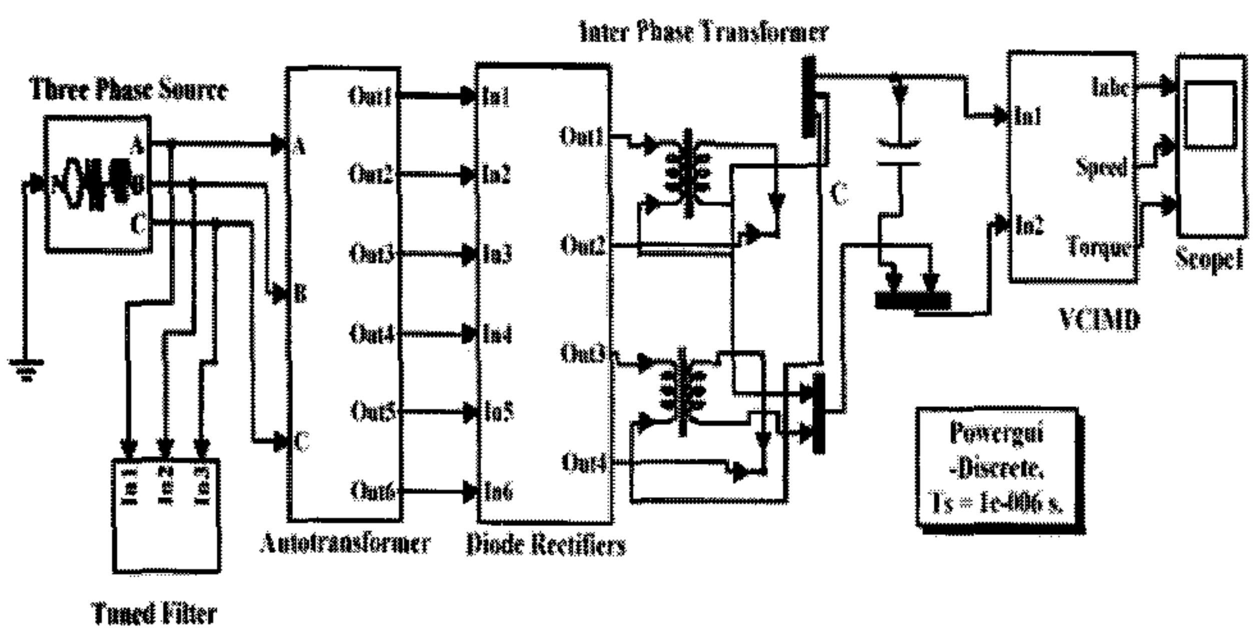

Fig. 5. MATLAB block diagram of proposed 12-pulse ac-dc converter based harmonic mitigator (Topology 'C') fed VCIMD.

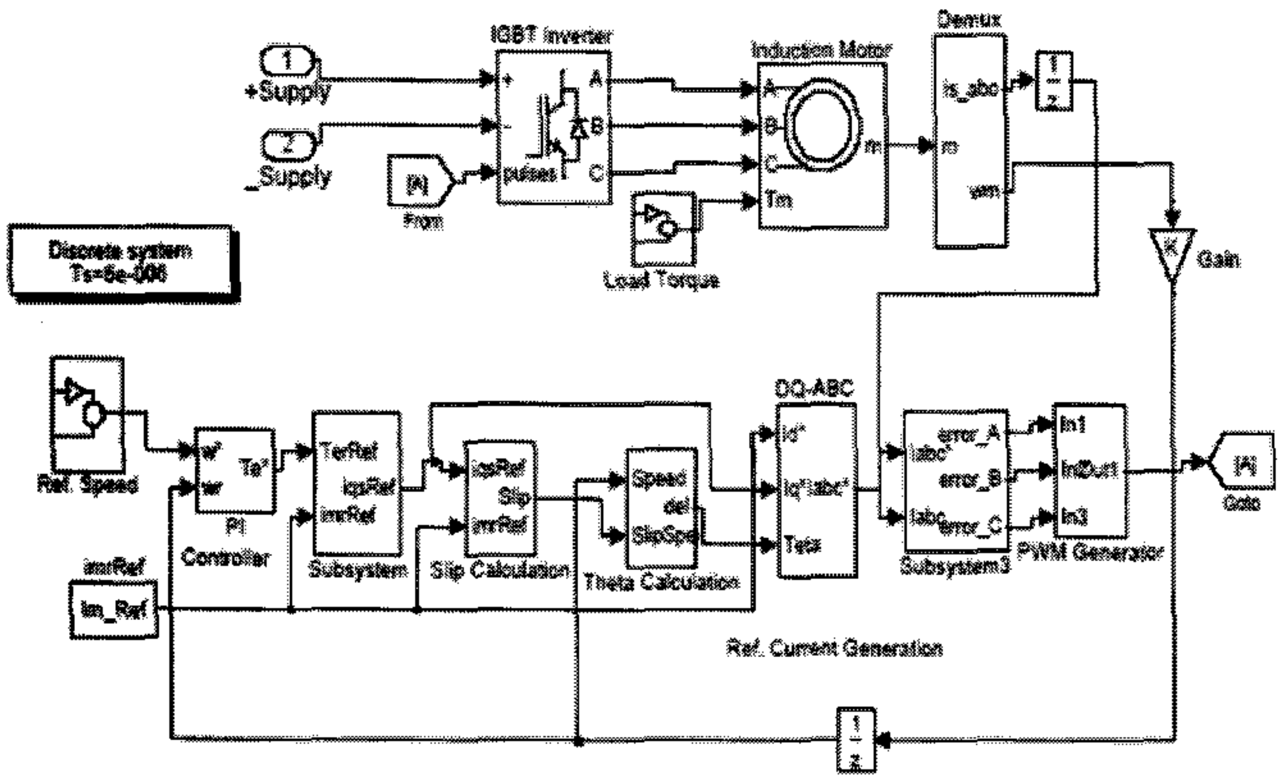

Fig. 6. MATLAB block diagram of vector controlled induction motor drive.

4. Experimentation

To verify the simulation model experimentally, a prototype of proposed autotransformer based 12-pulse based ac-dc converter as shown in Fig.3 is developed in the laboratory. The passive filter consisting of capacitors and a set of newly designed inductors is also developed to realize an 11^{th} 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 given below [15]:

Flux density= 0.8 Tesla, Current density= 2.3A/mm^2, Core Size= 8 No. Area of cross section of core = 3225mm^2 (50.8mm x 635mm). E-Laminations: Length = 184.1mm, width = 1714mm.

I-laminations: Length =171.4mm, width = 50.8mm. The number of turns of different windings (shown in Fig. 4a) and the conductor cross section for 12-pulse autotransformers is as follows: 12-Pulse autotransformer based AC-DC converter: N_1 = 68 (SWG = 13), N_2 = 68 (SWG = 13), N_3 = 22 (SWG = 13), N_4 = 429 (SWG = 18), N_5 = 22 (SWG = 13).

Various tests on 12-pulse and proposed ac-dc converters have been conducted at three-phase line voltage of 230V, 50Hz, and AC input with equivalent resistive loads. Recording of the results has been carried out using Fluke make power analyzer model 43B.

5. Results and Discussion

The proposed twelve-pulse ac-dc converters have been modeled and designed along with the VCIMD to suit retrofit applications for a 10hp induction motor. The simulations have been carried out in a MATLAB environment. The simulated results are verified on the developed prototype of the proposed ac-dc converter.

5.1 Simulation Results

Fig. 7 represents the dynamic performance of the 6-pulse ac-dc converter (Topology 'A') fed VCIMD at starting and load perturbation. The set of curves consists of supply voltage v_s, supply current i_{sa}, rotor speed 'ω_r' (in electrical rad /sec), three-phase motor currents i_{abcs}, motor developed torque 'T_e' (in N-m) and dc link voltage v_{dc} (V). Fig. 8 shows the supply current waveform along with its harmonic spectrum at full load, with THD of ac mains current as 30.7%, which deteriorates to 57.2% at light load (20% of full load) as indicated in Fig. 9. Moreover, the power factor at full load is 0.937, which deteriorates to 0.833 as the load is reduced to 20%, as shown in Table-I.

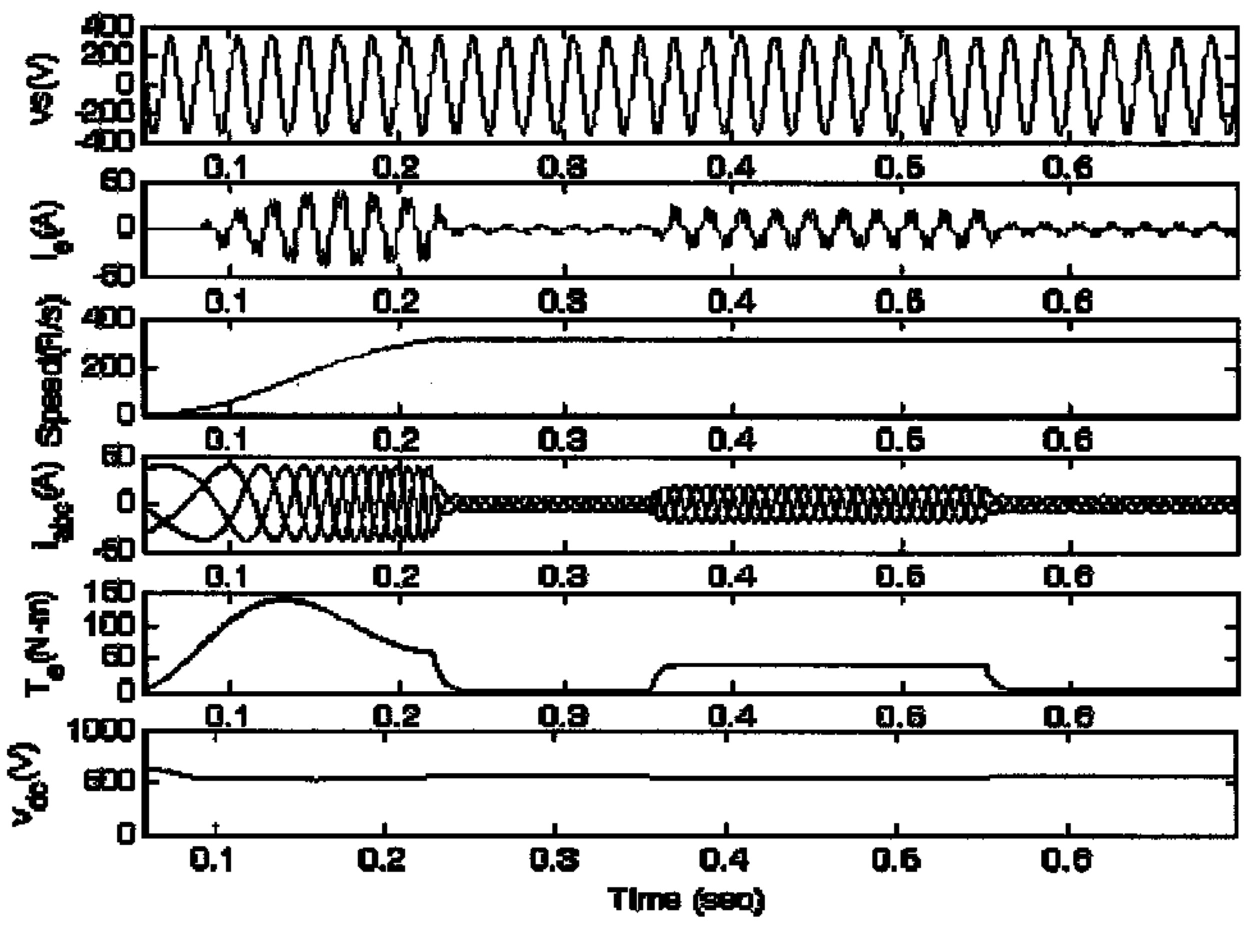

Fig. 7. Dynamic response of 6-pulse ac-dc converter fed VCIMD with load perturbation. (Topology 'A')

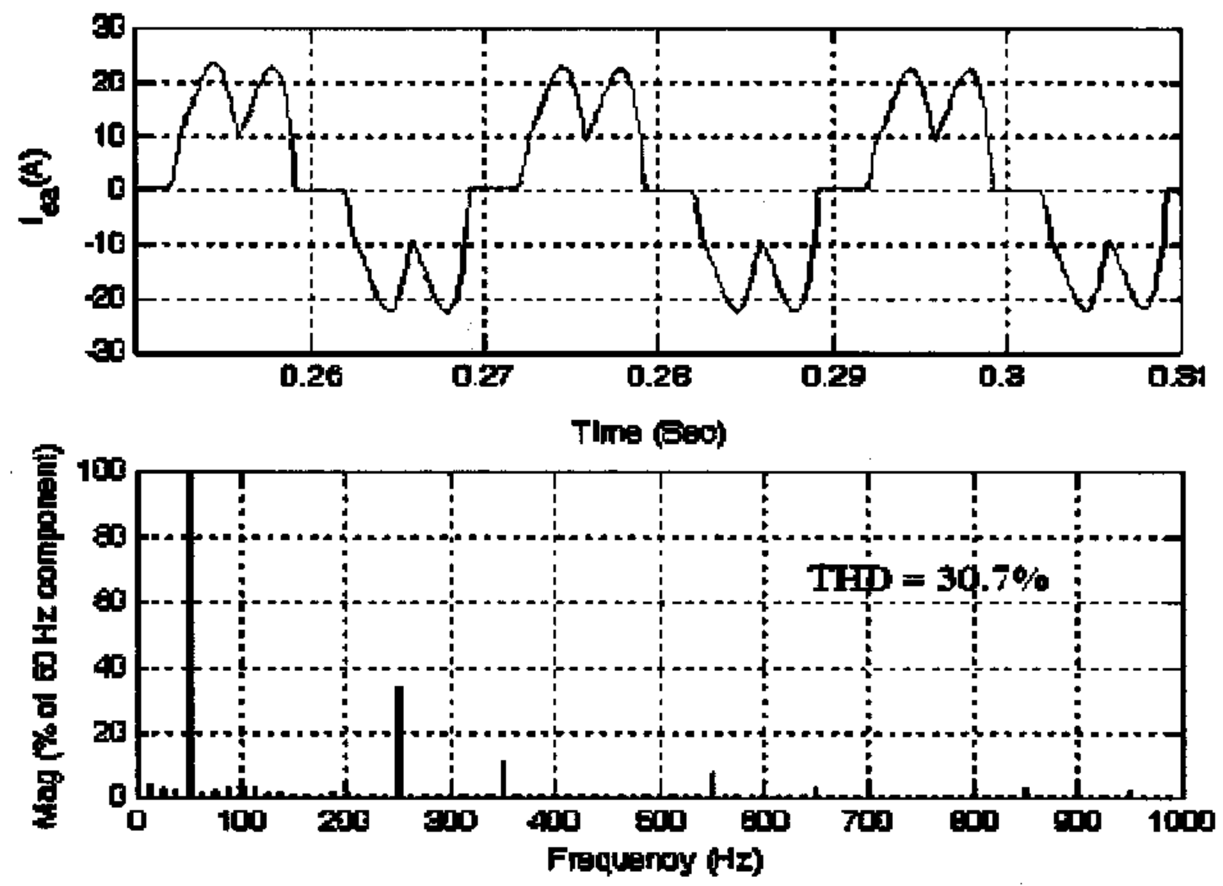

Fig. 8. AC mains current waveform of VCIMD fed by 6-pulse diode rectifier along with its harmonic spectrum at full load. (Topology 'A')

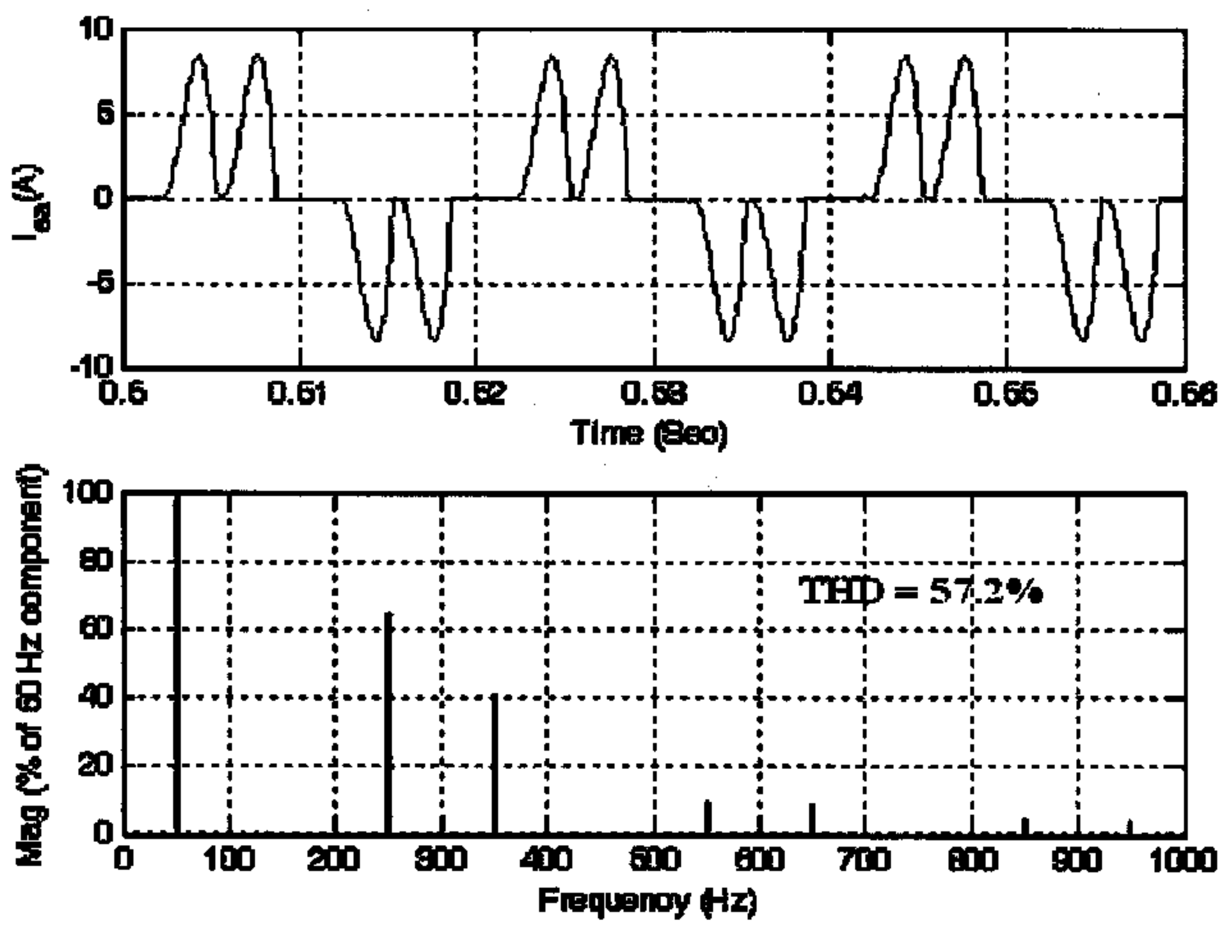

Fig. 9. AC mains current waveform of VCIMD fed by 6-pulse diode rectifier along with its harmonic spectrum at light load (20%) (Topology 'A').

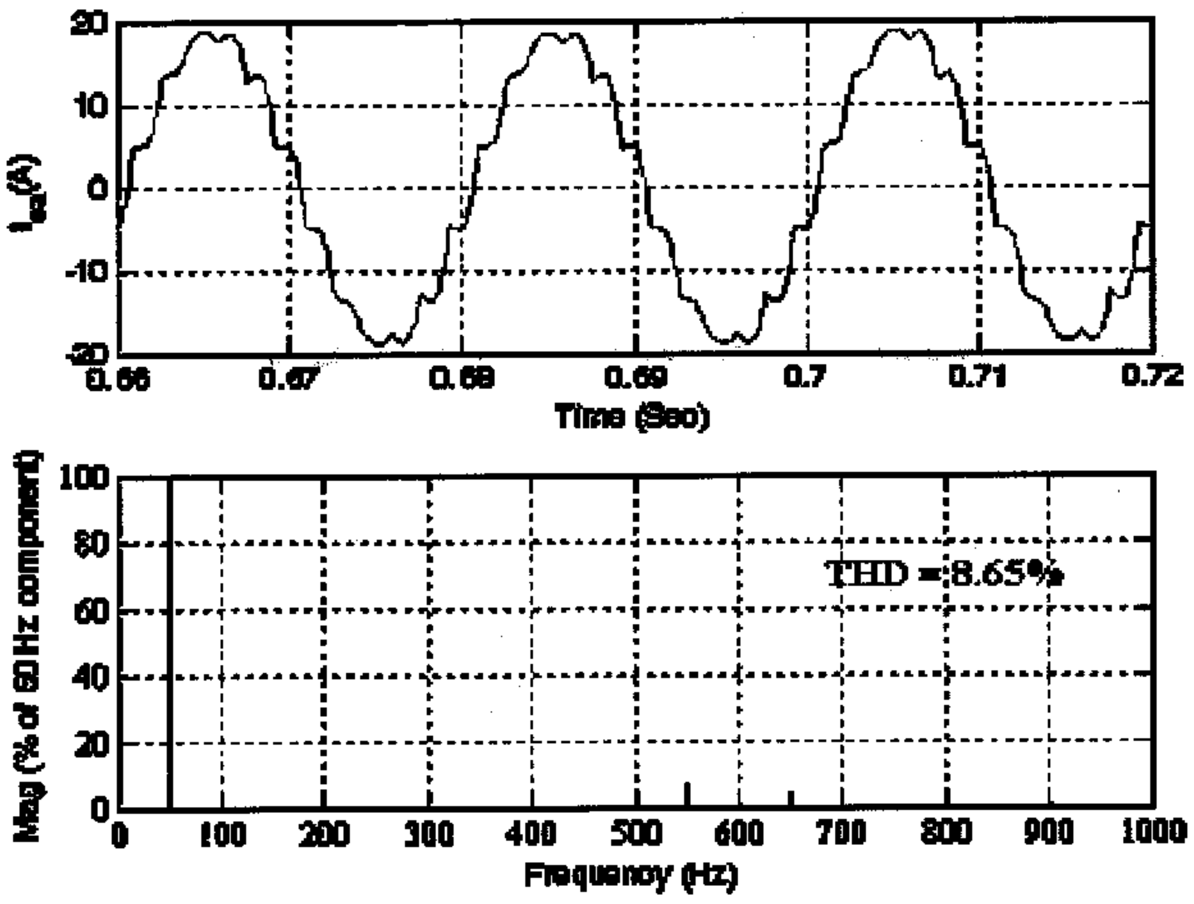

Fig. 10. AC mains current waveform alongwith its harmonic spectrum at full load for Topology 'B'.

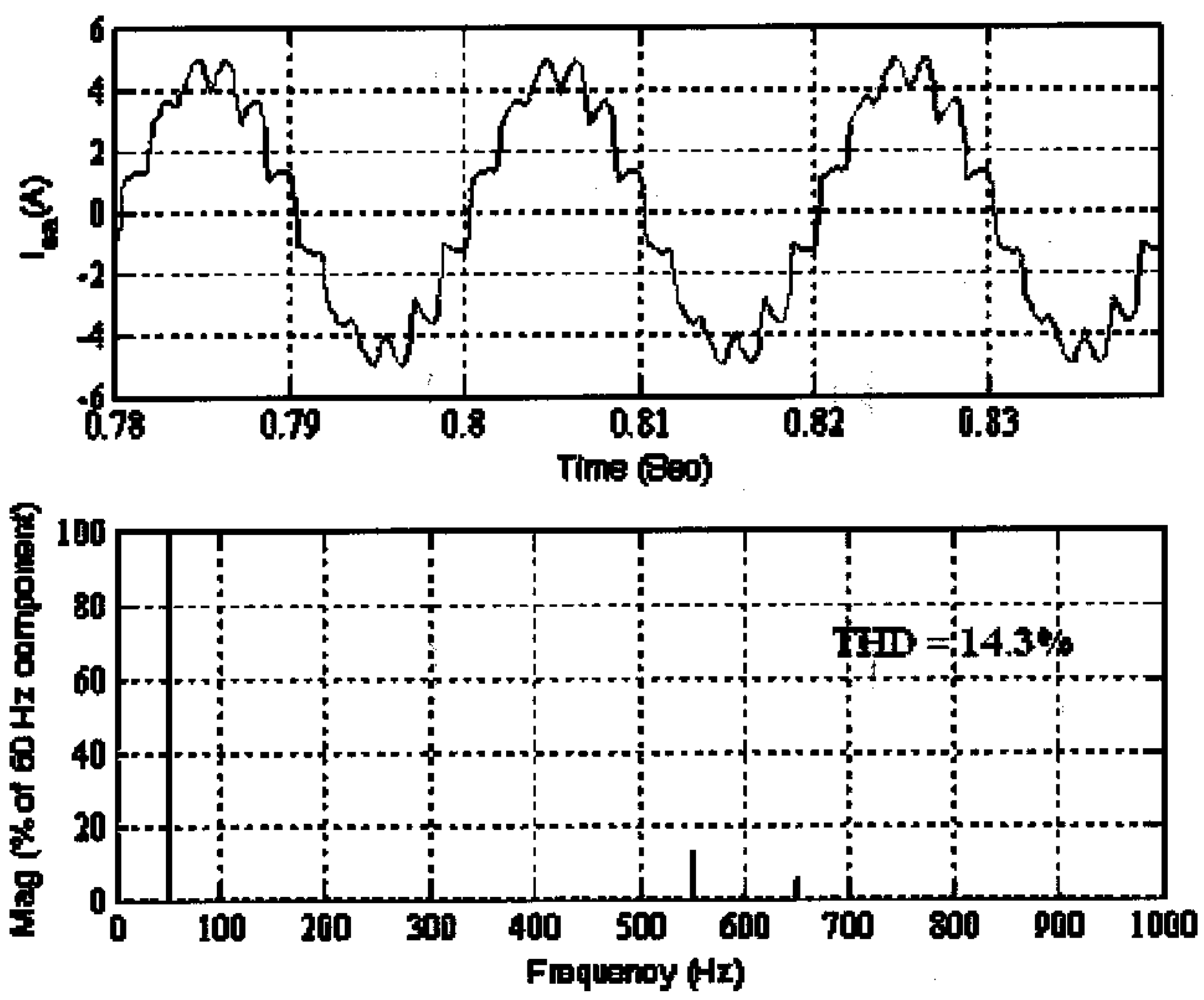

Fig. 11. AC mains current waveform alongwith its harmonic spectrum at light load (20%) for Topology 'B'.

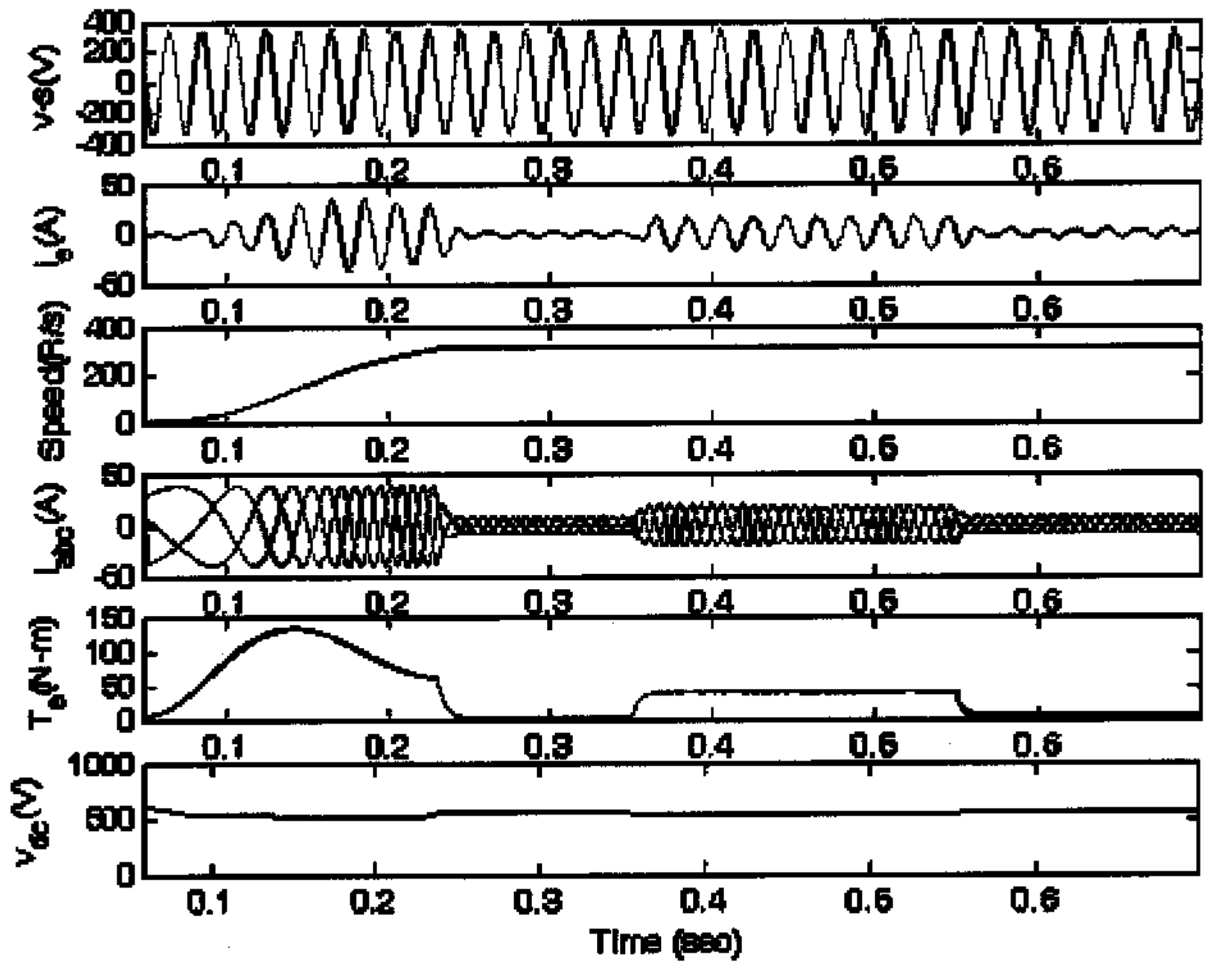

Fig. 12. Dynamic response of proposed ac-dc converter (Topology 'C') fed VCIMD with load perturbation.

TABLE 1. Comparison of Power Quality Parameters of a VCIMD Fed from Different ac-dc Converters

Sr. No.	Topo logy	THD of V_s (%)	Supply Current I_{sa} (A)		THD of I_{sa} (%)		Distortion Factor (DF)		Displacement Factor (DPF)		Power Factor (PF)		DC Link Voltage			
													Average (V)		Ripple factor (RF) (%)	
			FL	LL	FL	LL	FL	LL	FL	LL	FL	LL	FL	LL	FL	LL
1.	A	8.29	13.8	4.09	30.7	57.2	.955	.868	.980	.959	.937	.833	547	555	.122	.085
2.	B	2.69	13.2	3.46	8.70	14.3	.996	.993	.982	.990	.978	.984	547	556	.016	.0073
3.	C	2.20	12.6	3.50	2.20	6.35	.999	.998	.998	.942	.998	.940	546	560	.013	.006

FL: Full Load LL: Light Load (20% of full load)

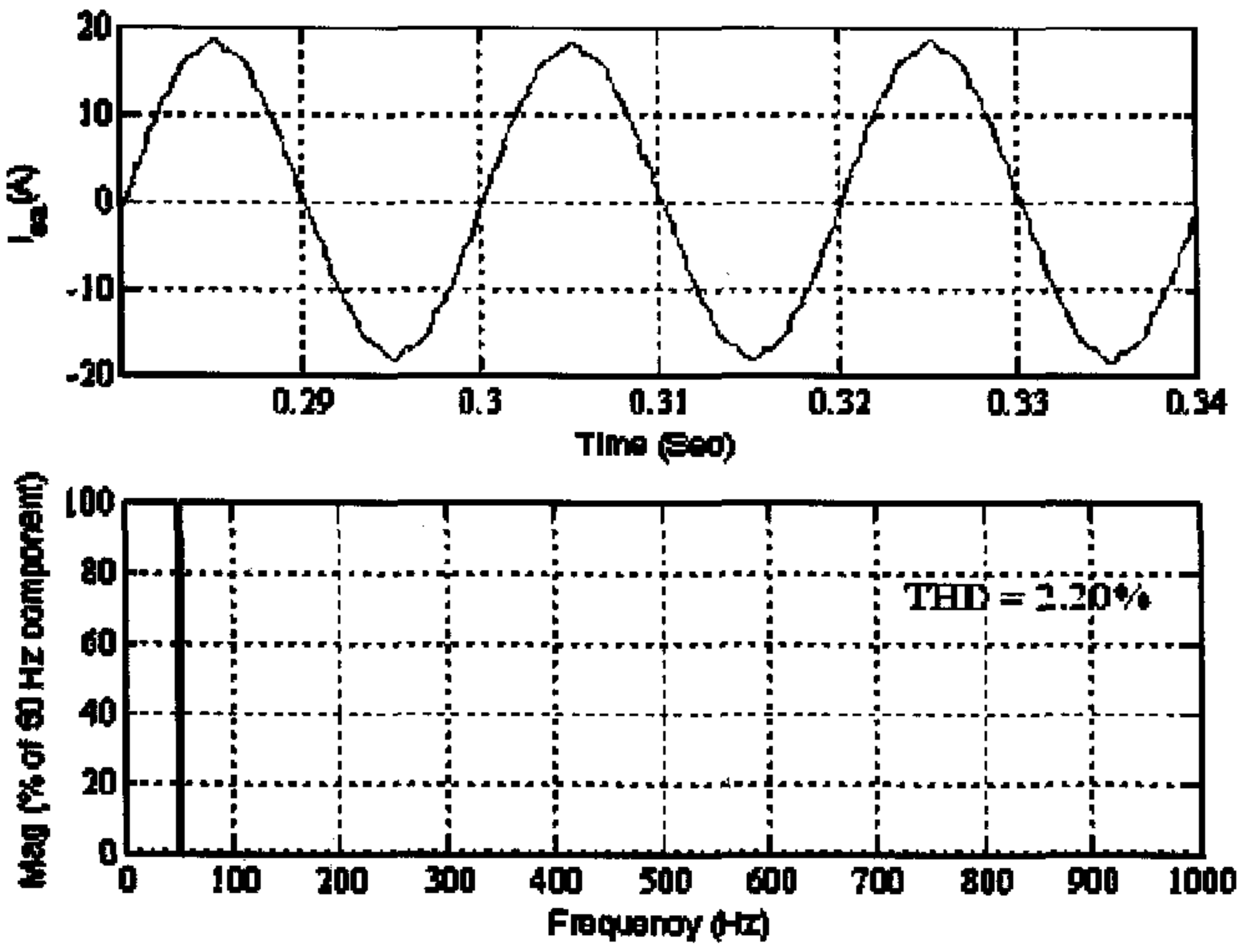

Fig. 13. AC mains current waveform along with its harmonic spectrum at full load for Topology ‘C’.

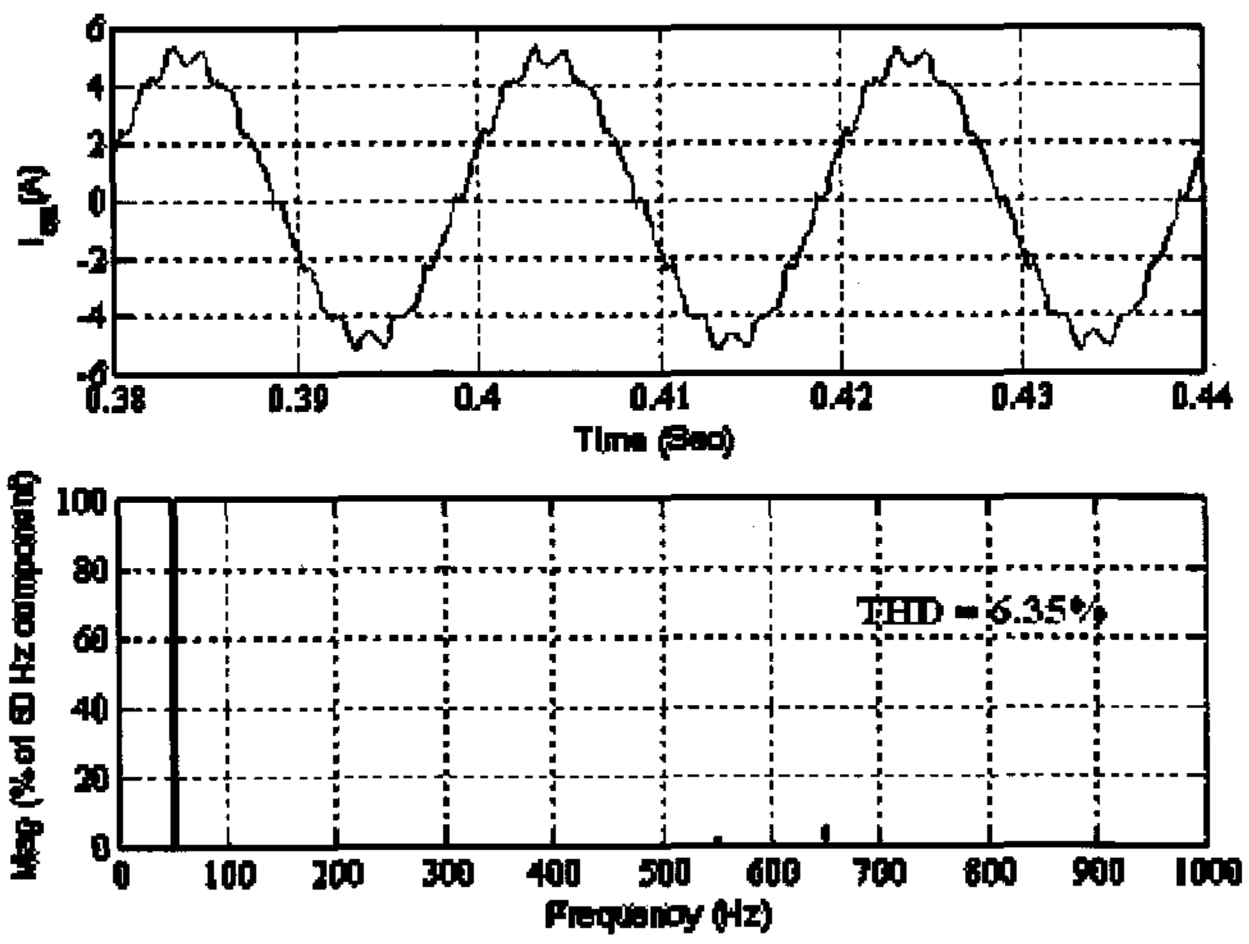

Fig. 14. AC mains current waveform along with its harmonic spectrum at light load (20%) for Topology ‘C’.

The performance of a twelve-pulse ac-dc converter feeding VCIMD is shown in Figs. 10-11. Fig. 10 reveals the supply current waveform along with its harmonic spectrum at full load, with THD of ac mains current as 8.70%, while Fig. 11 reveals supply current waveform along with its harmonic spectrum under light load conditions. At light load, the THD of ac mains current is observed to be 14.3% and the power factor is 0.984. These results demonstrate the need for improvement to meet IEEE 519 standard [4].

The performance of the proposed harmonic mitigator is shown in Figs. 12-14. Fig. 12 represents the dynamic performance of the proposed ac-dc converter (Topology ‘C’) fed VCIMD at starting and load perturbation. It shows the similarity in response as compared to that of a 6-pulse ac-dc converter fed VCIMD. The input current waveform has improved drastically, as indicated in Fig. 13 at full load and in Fig. 14 at light load condition. The THD of ac mains current at full load is 2.20% and that at light load is 6.35%. It shows that the THD of ac mains current is always within IEEE standard limits. The power factor is also improved, as can be seen. in Table-I.

To ensure that the proposed harmonic mitigator operates satisfactorily under varying load conditions, the load on VCIMD is varied. Table 2 shows the effect of load variation on VCIMD to study various power quality indices. It is seen from these results that the proposed harmonic mitigator performs well under load variation on VCIMD with a near unity power factor and THD of supply current always less than 8%.

On the magnetics side, the proposed 12-pulse based ac-dc converter (Topology ‘C’) needs an autotransformer of 2.86kVA, an interphase transformer (IPT) of 0.71kVA, and a passive filter of 1.7kVA, totaling to 50% of the load rating. The passive shunt tuned filter has been designed such that the ac mains current drawn does not increase with the addition of the harmonic filter. Table 3 shows the variation of supply current (I_{sa}) and converter input current (I_{ca}) with load on VCIMD. It can be observed that the supply current (I_{sa}) is mostly less than the converter input current (I_{ca}). This clearly signifies the effectiveness of the proposed harmonic mitigator.

Table 1 presents a comparative study of different power quality indices of a VCIMD fed from a 6-pulse converter, 12-pulse converter, and proposed 12-pulse based converter, showing a remarkable improvement in different power quality indices.

5.2 Experimental Validation

Different tests have been conducted on the developed prototype of the proposed harmonic mitigator. Fig. 15a shows the waveform of supply current at full load along with its harmonic spectrum of the 12-pulse ac-dc converter fed load. It shows the THD of ac mains current as 7.3%. Similarly, Fig. 15b indicates the waveform of the supply current along with its harmonic spectrum at light load. It depicts the THD of ac mains current as 11.1%. The effect of load variation on a 12-pulse ac-dc converter fed VCIMD is shown in Table 4. The results again validate the need of improving these parameters to satisfy the IEEE standard [4].

The test results on the proposed harmonic mitigator are shown in Fig. 16. At full load, the waveform of supply voltage V_{ab} (line-line) and third phase supply current I_{sc} along with its harmonic spectrum is given in Fig. 16a. It indicates the THD of ac mains current as 3.6%. Under light load condition, these waveforms are indicated in Fig.16b, revealing the THD of ac mains current as 7.8%. The effect of load variation on the proposed 12-pulse ac-dc converter fed VCIMD is shown in Table 5. It is observed from the Table 5, that the power factor is also improved to close to unity in the wide operating range of the load on VCIMD in the proposed ac-dc converter, apart from improvement in THD and CF of ac mains current.

6. Conclusions

A new12-pulse ac-dc converter with small rating passive filter feeding a VCIMD has been designed and analyzed in detail. The design technique of the proposed converter has shown the flexibility to design an autotransformer suitable for retrofit applications. It has been observed that the proposed harmonic mitigator performs well even during load variations on the converter. The proposed converter has resulted in a reduction in the rating of overall components. The experimental results on the developed prototype of the proposed converter have validated the operation as well as the improved performance of the proposed harmonic mitigator.

Appendix

1. Motor Specifications:

Three-Phase Squirrel Cage Induction Motor –10 hp (7.5kW), 3-Phase, 4 Pole, Y- connected, 415 V, 50 Hz, R_s = 1.0 ohms, R_r = 0.76 ohms, X_{ls} = 0.77 ohms, X_{lr} = 0.77 ohms, X_m = 18.84 ohms, J = 0.1 kg-m^2.

DC Link parameters: L_d = 0.3mH, C_d = 2200μF.

Controller Parameters: PI Controller: K_p = 45.0, K_i = 0.1. Passive filter components: R = 0.5 ohm, L = 4mH, C = 20μF.

2. Vector Controlled Induction Motor Drive

In vector control, an induction motor is controlled like a dc motor having independent signals for flux and torque control. In the rotor flux oriented reference frame, the reference flux component of the stator current i_{sx} is obtained as shown in (Fig.1):

$$i_{sx}^* = i_{mr} + \tau_r (\Delta i_{mr}/\Delta T) \quad (12)$$

The closed loop PI speed controller compares the reference speed (ω_r^*) with motor speed (ω_r) and generates reference torque T^* (after limiting it to a suitable value) as in (Fig.1):

$$T^*_{(n)} = T^*_{(n-1)} + K_p \{\omega_{e(n)} - \omega_{e(n-1)}\} + K_I \omega_{e(n)} \quad (13)$$

where, $T^*_{(n)}$ and $T^*_{(n-1)}$ are the output of the PI controller (after limiting it to a suitable value) and $\omega_{e(n)}$ and $\omega_{e(n-1)}$ refer to speed error at the nth and (n-1)th instants. K_p and K_I are proportional and integral gain constants. The y-component of the stator current i_{sy} is obtained from the output of the PI controller as:

$$i_{sy}^* = T^*/(k\, i_{sx}^*) \quad (14)$$

where k is a constant and it depends on the motor parameters.

These current components (i_{sx} and i_{sy}) are converted to stationary reference frame using rotor flux angle (Ψ) calculated as:

$$\Psi_{(n)} = \Psi_{(n-1)} + (\omega_2^* + \omega_r)\, \Delta T \quad (15)$$

where ω_2^* is slip frequency, which is expressed as:

$$\omega_2^* = i_{sy}^*/(\tau_r\, i_{sx}^*) \quad (16)$$

i_{mr} is the magnetizing current. $\Psi_{(n)}$ and $\Psi_{(n-1)}$ are value of rotor flux angles at nth and (n-1)th instants and ΔT is a sampling time taken as 100 μsecs.

These currents (i_{sx}^*, i_{sy}^*) are in synchronously rotating frame and are converted to stationary frame three phase currents (i_{as}^*, i_{bs}^*, i_{cs}^*) as given below:

$$i_{as}^* = -i_{sy}^* \sin\Psi + i_{sx}^* \cos\Psi \quad (17)$$

$$i_{bs}^* = \{-\cos\Psi + \sqrt{3}\sin\Psi\} i_{sx}^* (1/2) + \{\mathrm{Sin}\Psi + \sqrt{3}\cos\Psi\} i_{sy}^* (1/2) \quad (18)$$

$$i_{cs}^* = -(i_{as}^* + i_{bs}^*) \quad (19)$$

These reference currents (i_{as}^*, i_{bs}^*, i_{cs}^*) generated by vector controller and sensed winding currents (i_{as}, i_{bs}, i_{cs}) are fed to the PWM current controller which controls the

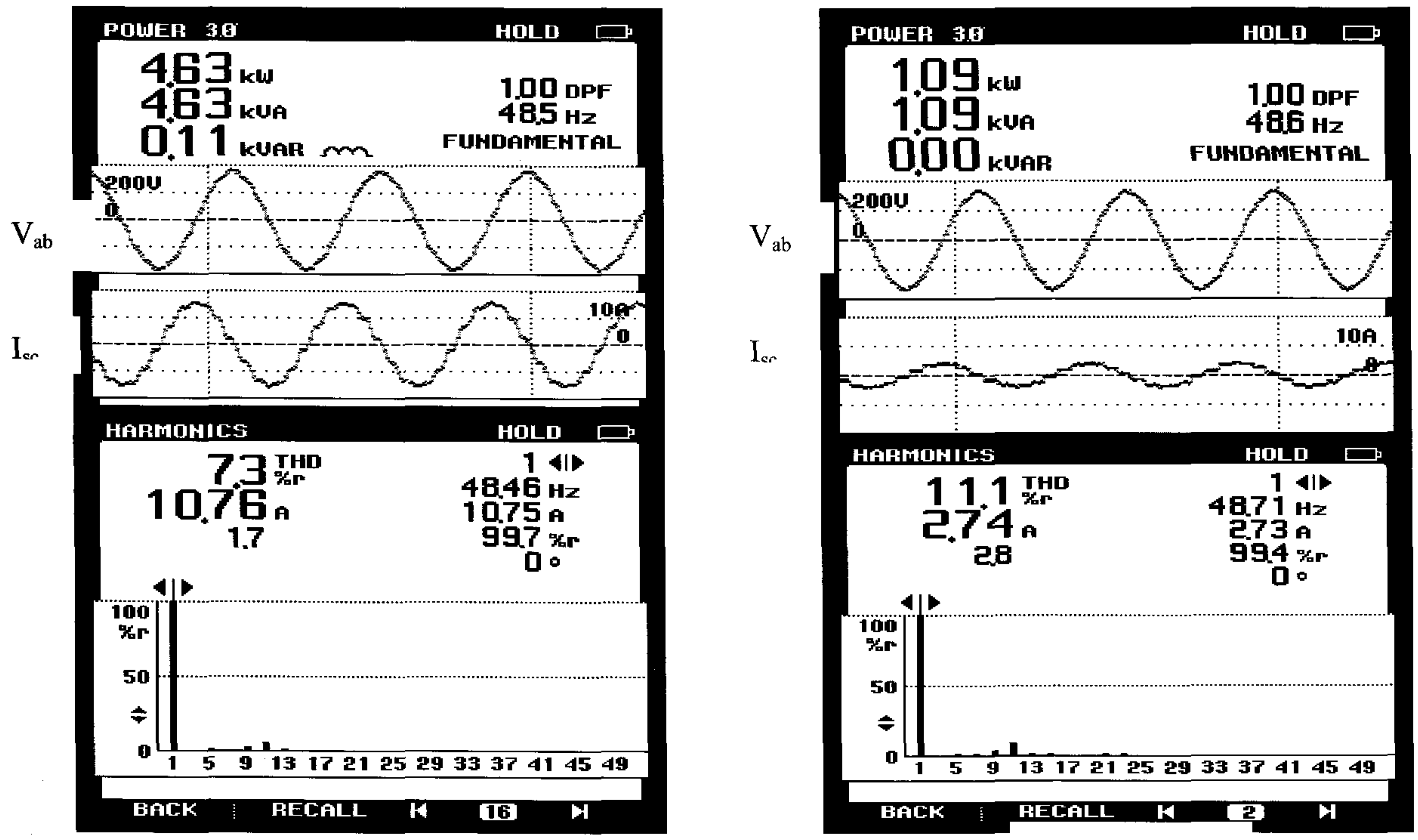

Fig.15 (a) Fig.15 (b)

Fig. 15. Recorded waveforms of 12-pulse ac-dc converter system (Topology 'B'). (a) supply voltage (V_{ab}), supply current waveforms (I_{sc}), and harmonic spectrum of supply current at full load, (b) supply voltage (V_s), supply current waveforms (I_{sc}), and harmonic spectrum of supply current at light load.

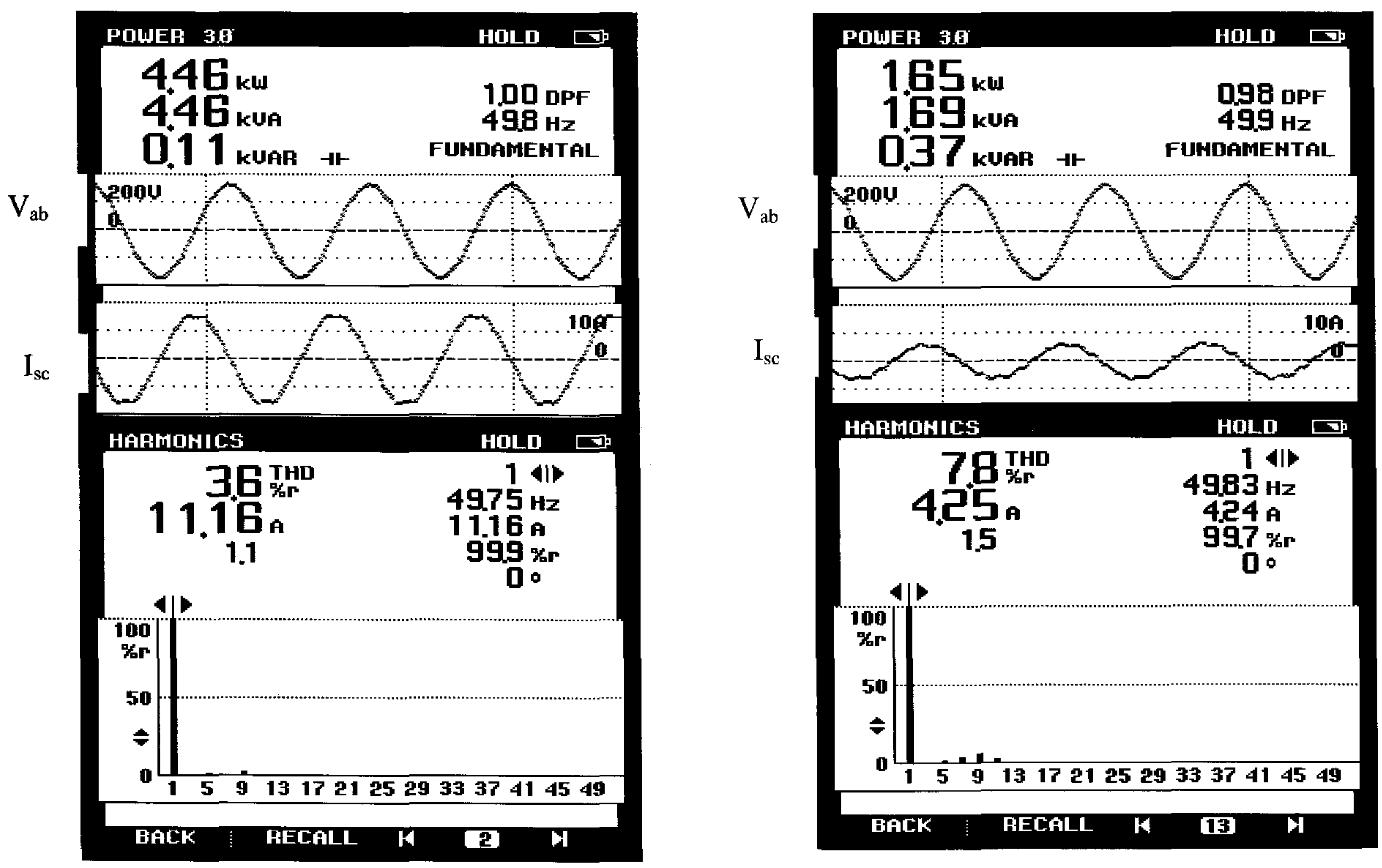

Fig.16 (a) Fig.16 (b)

Fig. 16. Recorded waveforms of proposed 12-pulse ac-dc converter system (Topology 'C') (a) supply voltage (Vab) and supply current waveforms (Isc) and harmonic spectrum of supply current at full load, (b) supply voltage (Vab) and supply current waveforms (Isc) and harmonic spectrum of supply current at light load.

TABLE 2. Comparison of Power Quality Indices of Proposed 12-pulse Harmonic Mitigator Fed VCIMD under Varying Loads

Load (%)	THD (%)		Crest Factor (CF) of I_{sa}	Distortion Factor (DF)	Displacement Factor (DPF)	Power Factor (PF)	Ripple Factor (%)	V_{dc} (V)
	I_{sa}	V_t						
20	6.35	1.09	1.50	.9978	.942	.940	.0073	556
40	4.45	1.29	1.50	.999	.9877	.9868	.010	553
60	3.35	1.52	1.47	.9994	.9982	.9977	.012	551
80	2.63	1.65	1.44	.9996	1.00	.9996	.013	549
100	2.20	1.75	1.43	.998	1.00	.998	.016	547

TABLE 3. Comparison of Supply Current and Converter Input Current in Different Converter Topologies under Varying Loads

Sr.No.	Load (%)	6-pulse converter	12-pulse converter	
		I_{sa} (A)	I_{sa} (A)	I_{ca} (A)
1	20	4.09	3.50	3.46
2	40	6.23	5.48	5.58
3	60	8.43	7.79	7.96
4	80	11.0	10.39	10.61
5	100	13.8	12.63	12.69

TABLE 4. Experimental Comparison of Power Quality Indices under Varying Loads in 12-pulse ac-dc Converter

Supply Current I_{sa} (A)	THD (%)		Crest Factor (CF) of I_{sa}	Distortion Factor (DF)	Displacement Factor (DPF)	Power Factor (PF)	V_{dc} (V)
	I_{sa}	V_s					
2.74	11.1	1.8	1.4	.993	1.00	0.993	305
4.60	10.0	2.1	1.4	.995	1.00	0.995	304
6.80	8.90	2.7	1.4	.996	1.00	0.996	301
8.30	8.0	2.8	1.4	.997	1.00	0.997	299
10.76	7.3	3.0	1.4	.997	1.00	0.997	294

TABLE 5. Experimental Comparison of Power Quality Indices under Varying Loads in Proposed ac-dc Converter

Supply Current I_{sa} (A)	THD (%)		Crest Factor (CF) of I_{sa}	Distortion Factor (DF)	Displacement Factor (DPF)	Power Factor (PF)	V_{dc} (V)
	I_{sa}	V_s					
4.25	7.80	2.0	1.4	.997	0.98	0.977	303
5.12	6.80	2.0	1.4	.997	0.99	0.987	302
6.92	5.20	2.0	1.4	.998	1.00	0.998	298
9.19	4.10	2.0	1.4	.999	1.00	0.999	294
11.16	3.60	1.9	1.4	.999	1.00	0.999	292

gating of IGBT's used in VSI. The PWM switching frequency is taken as 20kHz.The VSI generates PWM voltages being fed to the motor to develop the torque for running the motor at a desired speed under required loading conditions.

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