A Zigzag Connected Auto-Transformer Based 24-Pulse AC-DC Converter

Bhim Singh* and Sanjay Gairola†

Abstract – In this paper, a 24-pulse AC-DC converter is designed, modeled, simulated, and developed to feed non-isolated varying loads. The proposed AC-DC converter configuration consists of an auto-transformer based on zigzag connection to overcome current harmonic problems in AC mains. It improves power quality at AC mains and it meets IEEE-519 standard requirements at varying loads. A set of power quality indices on input AC mains and on DC buses for a load fed from 6-pulse and 12-pulse AC-DC converters is also given to compare their performance. It is observed that input current total harmonic distortion (THD) of less than 8% is possible with the proposed topology of AC-DC converter at varying loads.

Keywords: 24-pulse, AC-DC Converter, Power Quality, Zigzag Connection

1. Introduction

The current harmonics are problems in AC-DC converters because they cause increased losses in the customer and utility power system components. Distribution transformers are especially sensitive to this problem and may need to be derated to as much as 50% capacity when feeding loads with extremely distorted current waveforms (current Total Harmonic Distortion (THDi) above 100%). It is reported in ANSI/IEEE C 57.110-1986 (IEEE Recommended Practice for Establishing Transformer Capacity when Supplying Non-sinusoidal Load Currents) [1] that a transformer subjected to non-sinusoidal load currents having more than 5% THD needs to be derated. This is the reason that the transformers are specially designed (also called "K-factor" transformers) to feed non-sinusoidal loads. Induction motors are widely used in the industry (70-80% of motors are induction motors) and are also known as the main work-horses. The evolution of solid state converters has led to their use in variable frequency drives (VFDs) employing various control techniques such as vector control (VC) and direct-torque-control (DTC) due to their superior performance. These VFD's are generally fed by a 6-pulse diode bridge rectifier, which results in the injection of harmonic currents into AC mains and does not meet IEEE Standard 519-1992 [2] requirements. One such six-pulse diode bridge fed vector controlled induction motor drive (VCIMD) and the controller is shown in Fig. 1. The VFDs using different controllers are explained in the literature [3].

Six-pulse diode bridge rectifiers with delta and star connected transformers are described in the literature [4]. These diode bridges may be connected in series or parallel to form higher pulse AC-DC converters using six-pulse converters depending on output DC voltage requirement in a particular application. The harmonic pollution created by the non-linear loads must be checked and the standards regarding limiting harmonics are outlined by IEEE [2].

A star/fork transformer as a phase shifter for controlling the operation of a power transmission system of high-power carrying capacity has been described by Boshnyaga et al. [5]. A number of isolated and non-isolated AC-DC converters for improved power quality have been reported by Paice [6]. Appropriate fork connections as described by Paice [7] could be employed to provide 12-pulse and 18–pulse AC-DC converters for drive applications. A zigzag transformer based AC-DC converter has been reported by Owens [8]. Chen and Horng [9] have also described a 28-step current wave shaper for harmonic reduction. A fork-connection based 24-pulse AC-DC converter is also described by Singh et al. [10] for power quality improvement that employs the principle of DC ripple reinjection for pulse doubling in the 12-pulse AC-DC converter.

The harmonics in the input current and output voltage of conventional 12-pulse uncontrolled rectifiers can be reduced by using tuned passive filters. However, these filters are bulky and lossy. Moreover, some applications have stringent power quality specifications and it is inevitable to use a 24-pulse or higher pulse AC-DC converter system. Therefore, it is recommended that a higher pulse AC-DC converter must be used so that AC-

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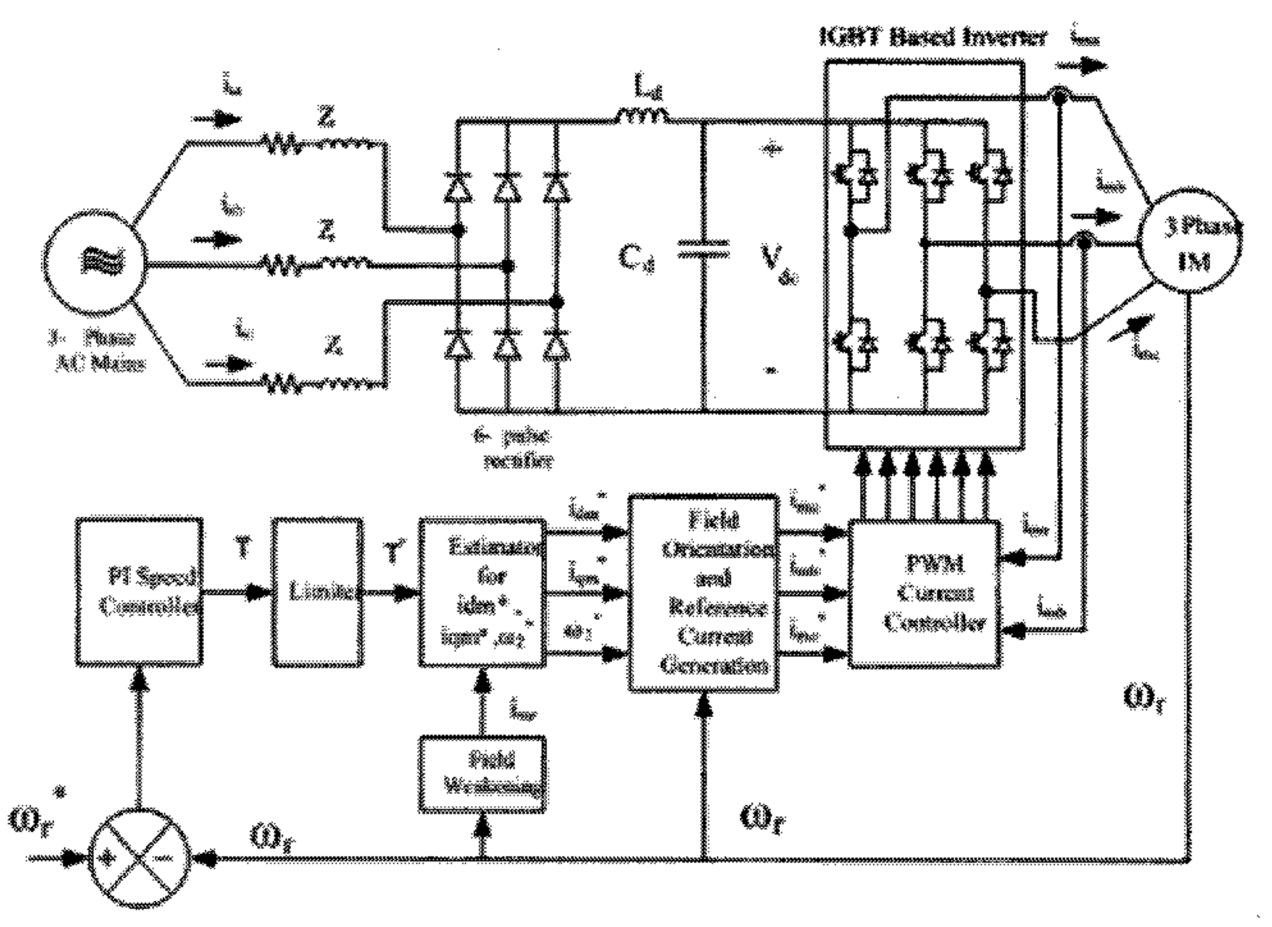

Fig. 1. A six pulse diode bridge fed vector controlled induction motor drive (VCIMD) and its controller.

DC conversion meets IEEE-519 standard requirements. With this in view, a 24-pulse AC-DC converter is designed and developed using zigzag connected auto-transformer.

In this paper, a zigzag autotransformer is proposed to produce four sets of phase staggered three-phase voltages. The secondary windings of unlike phases of different single-phase transformers are interconnected to form zigzag arrangement. The proposed autotransformer is capable of feeding four 6-pulse diode bridges, which are connected in parallel. This parallel connection produces a 24-pulse AC-DC converter configuration. A detailed design of the 24-pulse rectifier system is carried out to study the behavior of the proposed AC-DC converter under varying loads. The designed AC-DC converter system is modeled and simulated in MATLAB and its performance is evaluated to demonstrate power quality improvement at AC mains. The prototypes of 12-pulse and proposed 24-pulse AC-DC converters are developed in a laboratory to validate the developed models and their design.

2. Proposed 24-pulse AC-DC converter

Fig. 2 shows a 12-pulse AC-DC converter. This topology uses a zigzag-transformer that feeds two six-pulse diode bridge converters, which are connected on the DC side by inter-phase transformers.

The zigzag autotransformer winding arrangement for a 24-pulse AC-DC converter is shown in Fig. 3a and its connection along with a phasor diagram is shown in Figs.

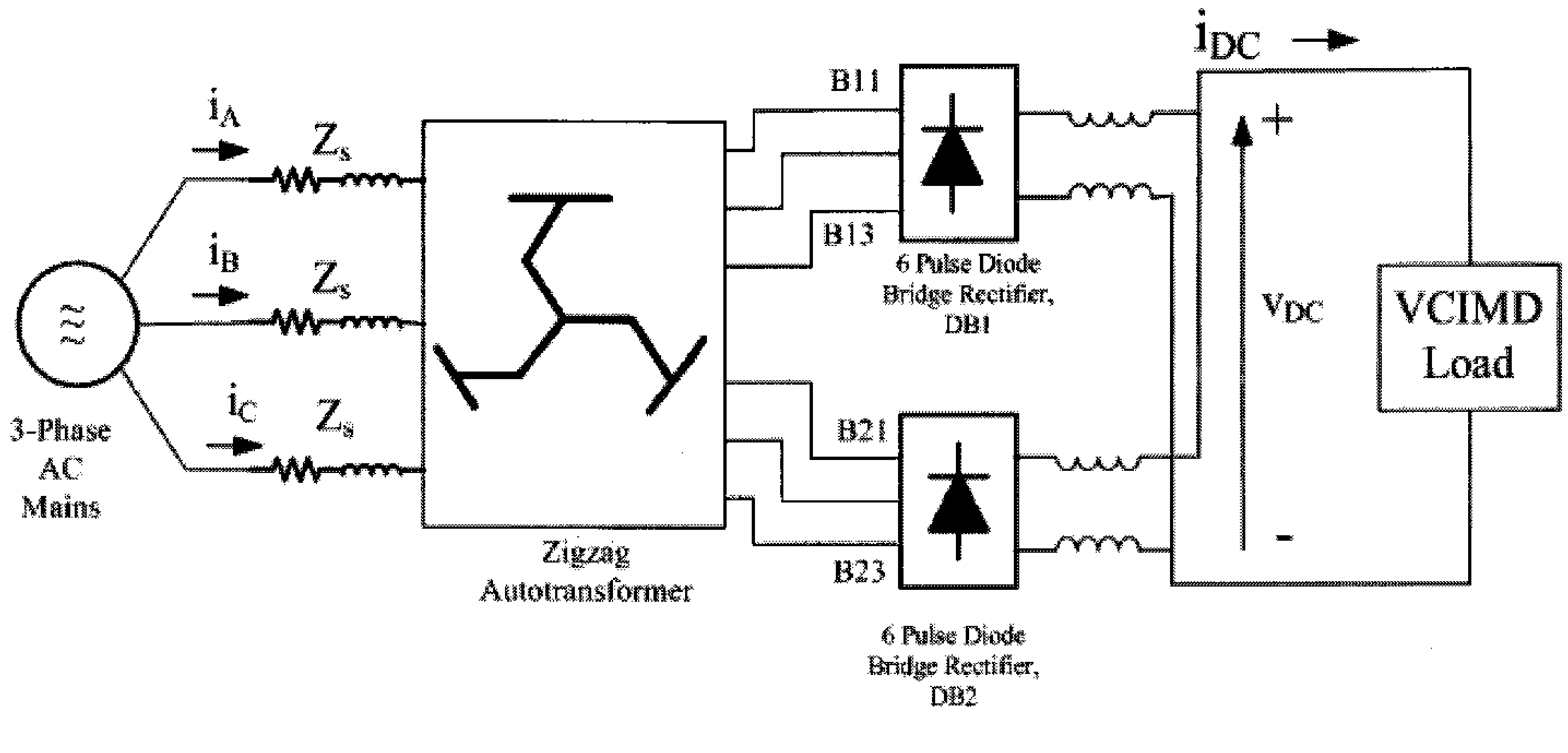

Fig. 2a. A 12-pulse AC-DC converter based on fork-transformer.

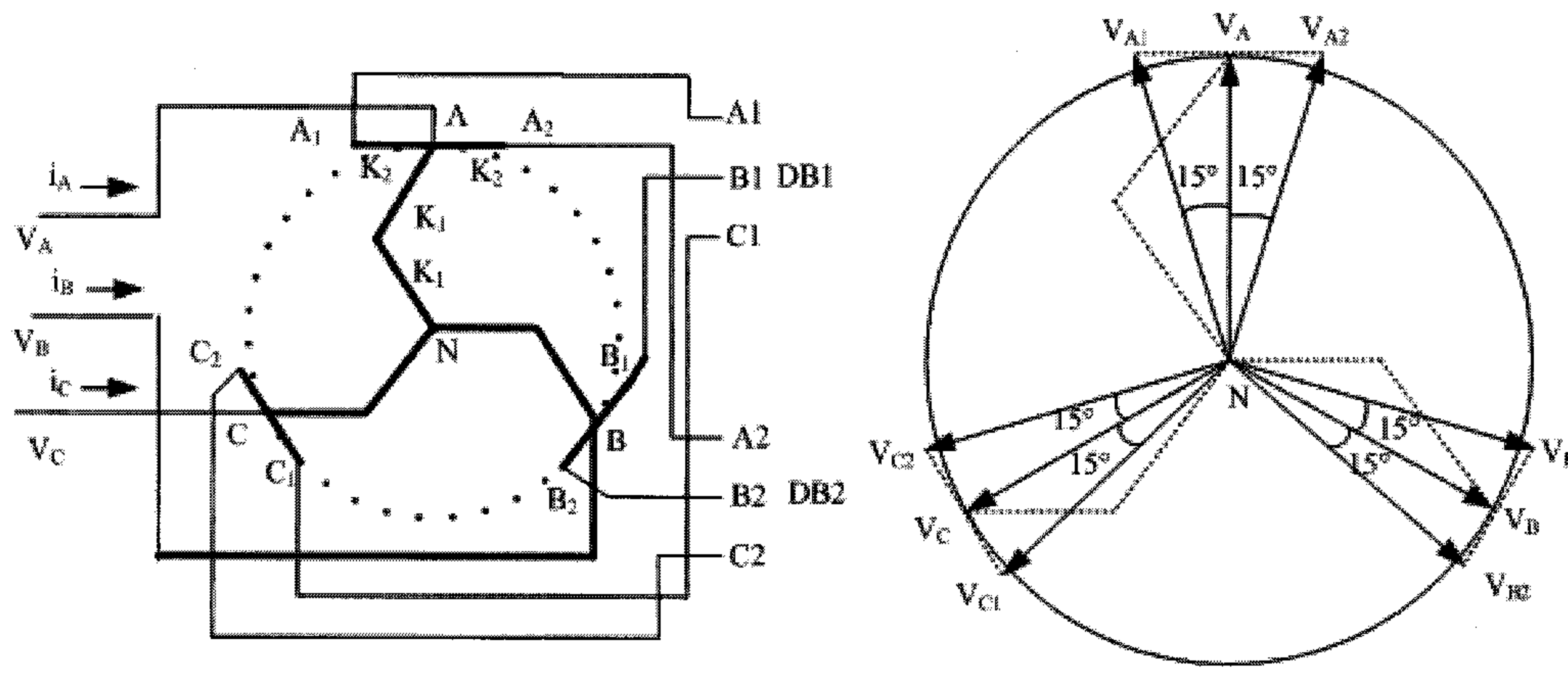

Fig. 2b. A 24-pulse AC-DC converter based on fork-transformer configuration.

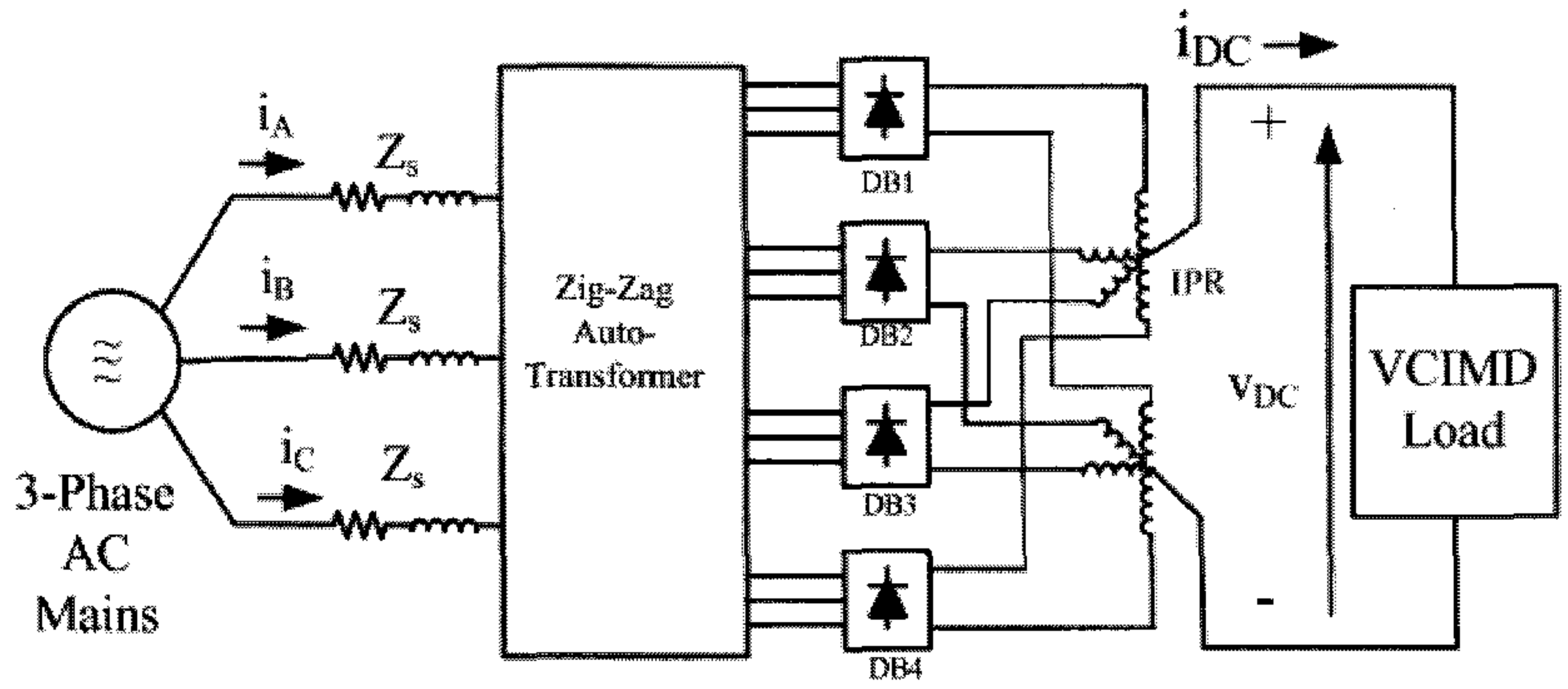

Fig. 3a. Twenty four-pulse AC-DC converter based on zigzag-transformer configuration.

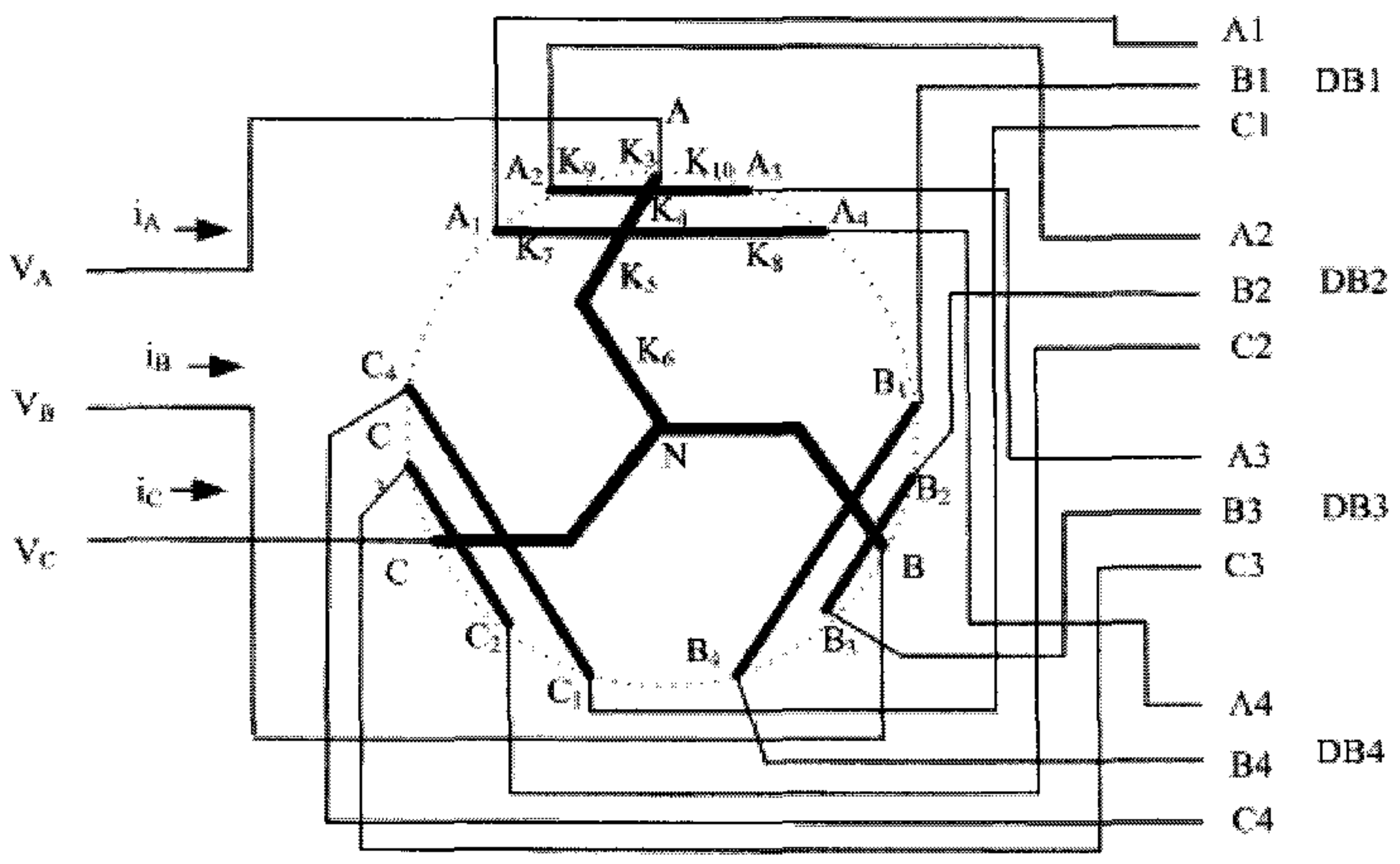

Fig. 3b. Zigzag autotransformer winding arrangement for 24-pulse AC-DC converter.

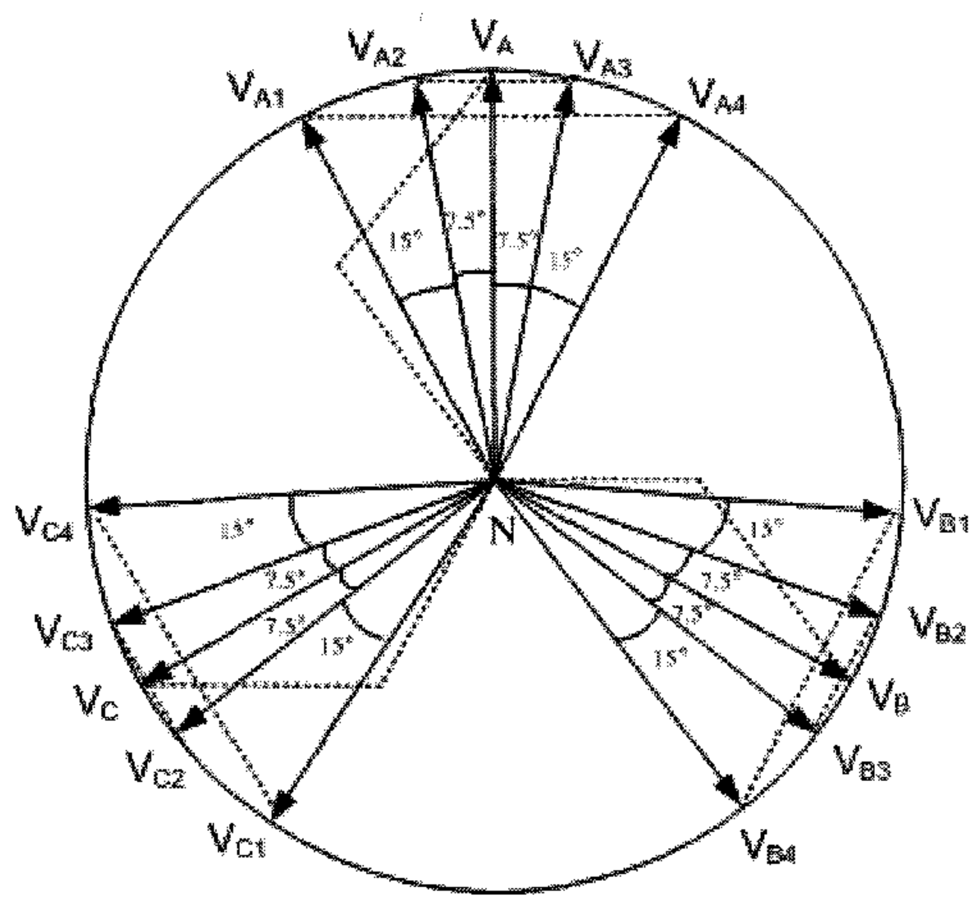

Fig. 3c. Phasor representation of transformer for 24-pulse AC-DC converter having fork connected windings.

3b and 3c. The four sets of output three-phase voltages produced are displaced at an angle of 15°. Two of these sets are displaced at an angle of ±7.5° from input phase voltage while the remaining two sets are displaced by ±22.5°.

2.1 Design of zigzag autotransformer for 12-Pulse AC-DC Converter

Fig. 2 shows the schematic of the zigzag-connected autotransformer for a 12-pulse AC-DC converter. The number of turns for its windings is determined as a function of the input phase voltage, V_A using the following relations.

Assume that the following set of three-phase supply voltages is applied to the input of autotransformer as follows:

$$V_A = V_S\angle 0^0,\quad V_B = V_S\angle -120^0,\quad V_C = V_S\angle 120^0$$
$$V_{AB} = \sqrt{3}V_S\angle 30^0,\quad V_{BC} = \sqrt{3}V_S\angle -90^0,\quad V_{CA} = \sqrt{3}V_S\angle 150^0 \quad (1)$$

Moreover, from Fig. 2b, the output voltages of this configuration are expressed as:

$$V_{A1} = K_1(V_{AB} - V_{CA}) - K_2V_{BC} \quad (2)$$

$$V_{A2} = K_1(V_{AB} - V_{CA}) + K_2V_{BC} \quad (3)$$

The values of these constants K_1 and K_2 determine the winding turns as a fraction of input phase voltage for the 12-pulse AC-DC converter. The values calculated are:

$$K_1=0.5773, \qquad K_2= 0.2588 \quad (4)$$

2.2 Design of zigzag autotransformer for 24-Pulse AC-DC Converter

Figs. 3(b) and 3(c) show the schematic of the zigzag arrangement and its graphical representation depicting the angular position of various phasors. The number of turns for every winding is determined as a function of the input phase voltage, V_A. These winding voltages, as marked in Figs. 3b and 3c, are expressed by the following relationships.

Consider that the input phase voltage is V_A (=$V_{AC}/\sqrt{3}$) and four sets of three-phase voltages fed to each bridge DB1 to DB4 are V_{A1}, V_{B1}, V_{C1}; V_{A2}, V_{B2}, V_{C1}; V_{A3}, V_{B3}, V_{C3}; and V_{A4}, V_{B4}, V_{C4} respectively.

The four sets of required voltages for the converters DB1 to DB4 are:

$$V_{A1} = V_S\angle 22.5^0, V_{B1} = V_S\angle -97.5^0, V_{C1} = V_S\angle -217.5^0 \quad (5)$$

$$V_{A2} = V_S\angle 7.5^0, V_{B2} = V_S\angle -112.5^0, V_{C2} = V_S\angle -232.5^0 \quad (6)$$

$$V_{A3} = V_S\angle -7.5^0, V_{B3} = V_S\angle -127.5^0, V_{C3} = V_S\angle -247.5^0 \quad (7)$$

$$V_{A4} = V_S\angle -22.5^0, V_{B4} = V_S\angle -142.5^0, V_{C4} = V_S\angle -262.5^0 \quad (8)$$

The output voltages can also be expressed as follows:

$$V_{A1} = -K_5V_{CA} + K_6V_{AB} - K_7V_{BC} \quad (9)$$

$$V_{A2} = -(K_4 + K_5)V_{CA} + K_6V_{AB} - K_9V_{BC} \quad (10)$$

$$V_{A3} = -(K_4 + K_5)V_{CA} + K_6V_{AB} + K_{10}V_{BC} \quad (11)$$

$$V_{A4} = -K_5V_{CA} + K_6V_{AB} + K_{10}V_{BC} \quad (12)$$

$$K_3+K_4+K_5= K_6 \quad (13)$$

Eqns. (6-13) give the values of constants K_3 to K_{10} for desired phase shift as:

$$K_3=0.01, K_4=0.0779, K_5= 0.4894, K_6= 0.5773,$$
$$K_7= 0.3387, K_8 =0.1255, K_9=0.1355, K_{10}=0.4266 \quad (14)$$

The values of these constants K_3 to K_{10} determine the winding turns as a fraction of input phase voltage. These values are used for the simulation of the proposed 24-pulse AC-DC converter.

3. MATLAB Based Simulation

A set of 6-pulse, 12-pulse and 24–pulse AC-DC converters are modeled and simulated in a MATLAB environment along with Simulink and Power System Blockset (PSB) toolboxes. The AC-DC converter feeds the VCIMD (Vector Controlled Induction Motor Drive) load (7.5kW) with an input of 415V, 50Hz AC supply and detailed data are given in the Appendix.

The MATLAB model of a 24-pulse AC-DC converter is shown in Fig. 4a. Fig. 4b presents a MATLAB model of an autotransformer for the 24-pulse AC-DC converter. The results obtained from the simulations for the proposed 12-pulse and 24-pulse AC-DC converters are given in Tables 1-2. The resulting waveforms for the 6-pulse and 24-pulse AC-DC converters at full-load along with VCIMD transient response for load perturbation are shown in Figs. 5-6. The waveform of AC mains current, harmonic spectra, and THD are shown in Figs. 7-9 for 6-pulse, 12-pulse, and 24-pulse AC-DC converters respectively. Table 2 compares the power quality parameters of 6-pulse, 12-pulse, and 24-

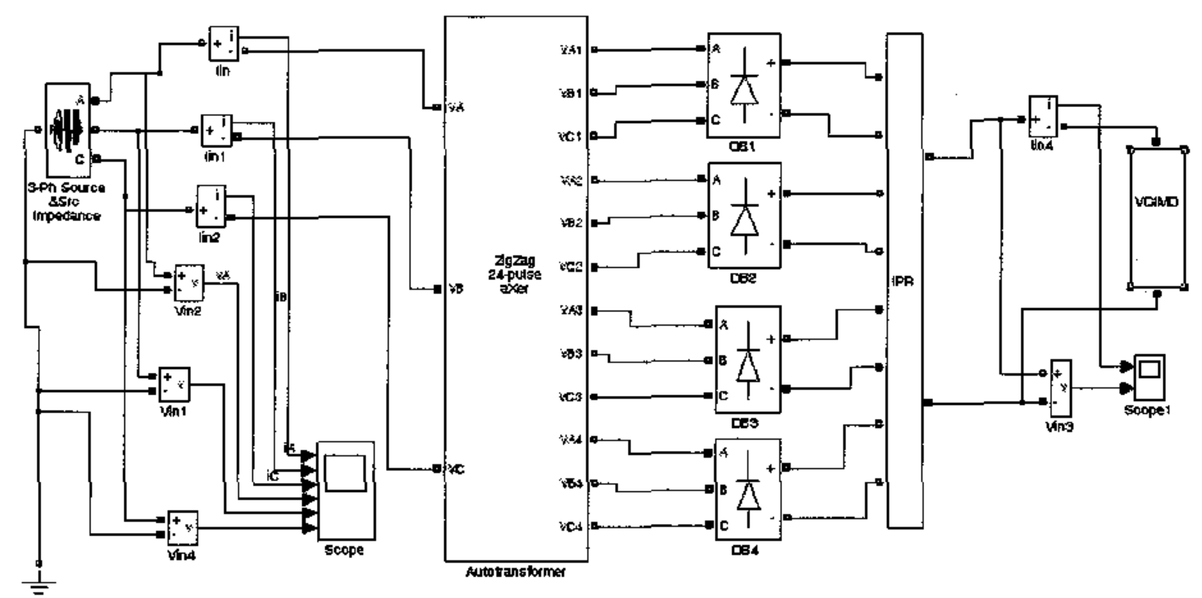

Fig. 4a. MATLAB model of 24-pulse AC-DC converter with VCIMD load.

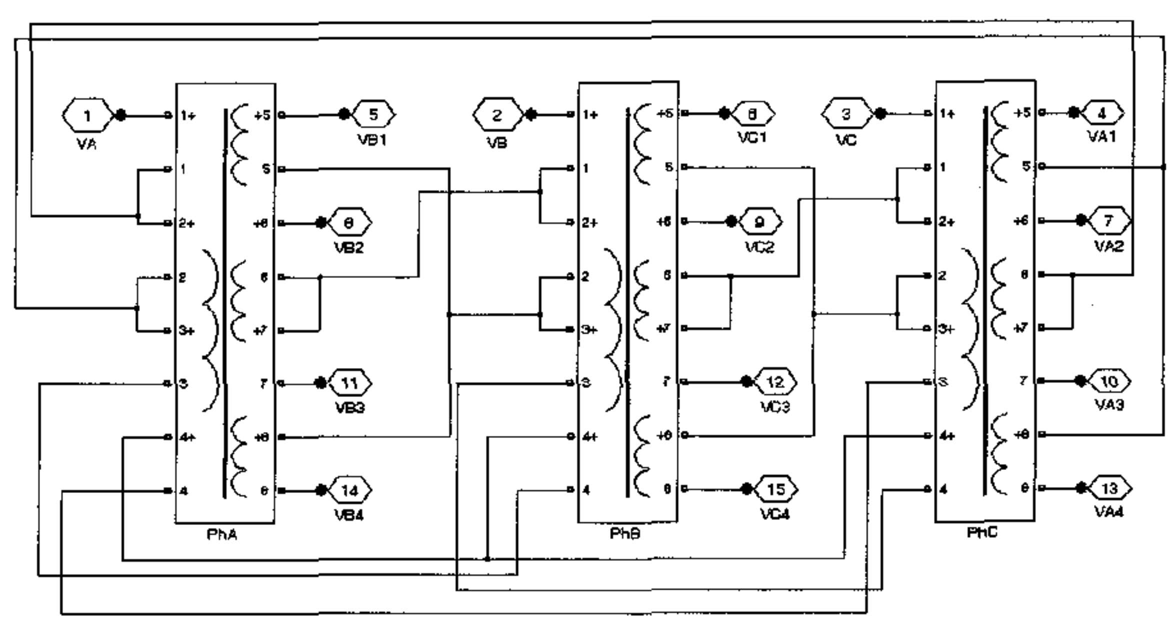

Fig. 4b. MATLAB model of auto-transformer for the 24-pulse AC-DC converter system simulation.

Table 1. Comparison of power quality parameters of 12-pulse and 24-pulse AC-DC converters.

Sr. No.	Topology	Load	THD of V_{ac} (%)	AC Mains Current I_{ac} (A)	THD of I_{ac}(%)	Distort-ion Factor, DF	Displacement Power Factor, DPF	Power Factor, PF	DC Voltage (V)	Load Current I_{dc} (A)	Ripple Factor, RF (%)
1	12-pulse Converter	20%	2.851	8.578	9.697	0.9946	0.9893	0.9840	555.7	10.28	0.006
		40%	3.494	11.03	9.533	0.9948	0.9897	0.9846	554.2	13.21	0.002
		60%	3.981	13.58	9.363	0.9948	0.9899	0.9848	552.6	16.48	0.004
		80%	4.674	16.22	9.179	0.9946	0.9900	0.9847	551.0	19.85	0.003
		100%	5.224	18.87	8.98	0.9946	0.9898	0.9845	549.4	23.24	0.002
2	24-pulse Converter	20%	2.028	8.378	3.974	0.9990	0.9931	0.9921	578.2	10.25	0.0002
		40%	2.286	10.73	3.763	0.9988	0.9922	0.9910	576.4	13.14	0.0001
		60%	2.550	13.31	3.556	0.9992	0.9910	0.9902	574.5	16.33	0.002
		80%	2.785	16.00	3.376	0.9990	0.9901	0.9891	572.7	19.66	0.003
		100%	3.036	18.74	3.221	0.9991	0.9891	0.9882	570.7	23.04	0.002

Table 2. Comparison of power quality parameters of different AC-DC converters.

Sr. No.	Topo-logy	% THD of V_{ac}	AC Mains Current I_{ac} (A)		% THD of I_{ac} at		Distortion Factor DF		Displacement Power Factor DPF		Power Factor PF		DC Voltage (V)	
			Light Load	Full Load	Light Load	Full Load	Light Load	Full Load	Light Load	Full Load	Light Load	Full Load	Light Load	Full Load
1	6-pulse	10.58	8.701	19.12	74.68	31.24	0.9110	0.9491	0.9798	0.9768	0.8926	0.9271	552.9	542.8
2	12-pulse	5.224	8.578	18.87	9.697	8.98	0.9946	0.9946	0.9893	0.9898	0.9840	0.9845	555.7	549.4
3	24-pulse	3.036	8.378	18.74	3.974	3.221	0.9990	0.9991	0.9931	0.9891	0.9921	0.9882	578.2	570.7

pulse AC-DC converters at light-load (20% of full-load) and full-load. The magnetic rating involved in these two topologies is given in Table 3.

4. Results and Discussion

The power quality indices of 12-pulse and 24-pulse AC-DC converters are given in Table 1. The waveform of AC mains current has improved in the 24-pulse AC-DC converter. The simulation results show that THDi (total harmonic distortion of AC mains current) at full-load in the 24-pulse AC-DC converter is 2.98%. These results clearly indicate that the 11th and 13th dominant harmonics of 12-pulse AC-DC converter are suppressed in 24-pulse AC-DC converters (Figs. 8-9).

The power quality indices THD_i, THD_v, distortion factor (DF), displacement factor (DPF), and power factor (PF) are also obtained at varying loads in 12-pulse and 24-pulse AC-DC converters. The comparison of power quality indices obtained for proposed 12-pulse and 24-pulse AC-DC converter topologies is also made with a 6-pulse AC-DC converter and these are given in Table 2. It can be seen that the performance of a 24-pulse AC-DC converter in terms of current THD and power factor have improved and the waveforms and harmonic spectrum of AC mains

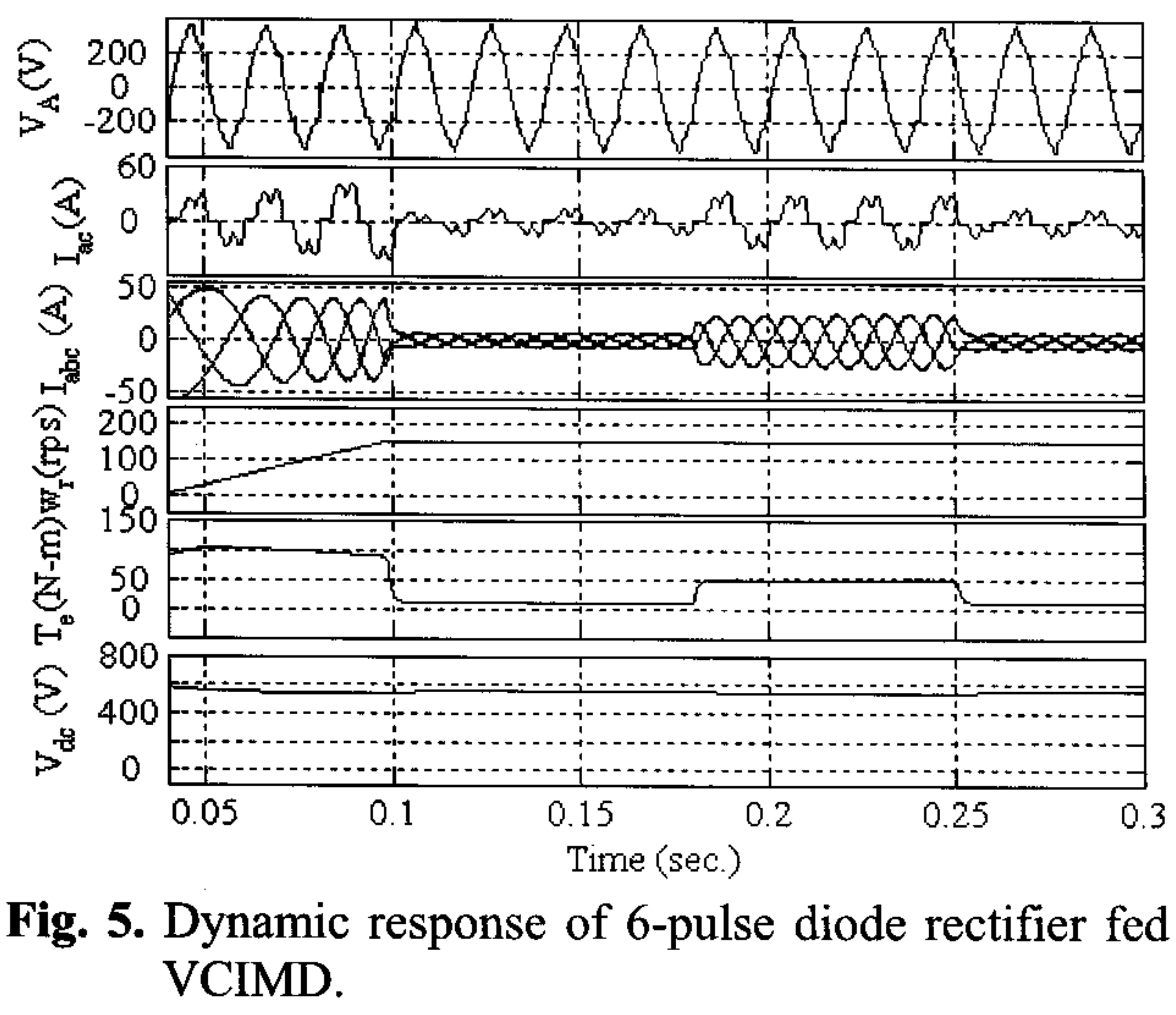

Fig. 5. Dynamic response of 6-pulse diode rectifier fed VCIMD.

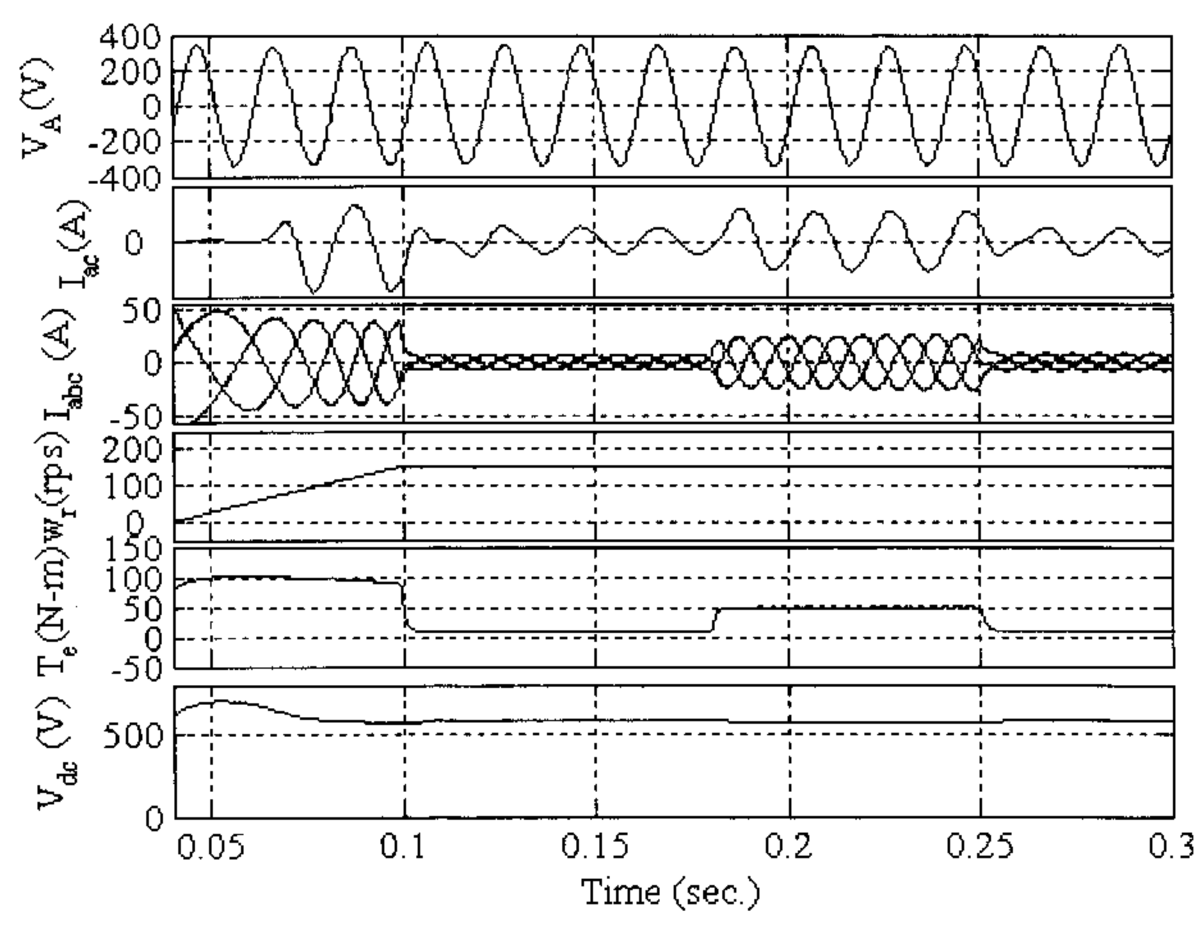

Fig. 6. Dynamic response of 24-pulse diode rectifier fed VCIMD with load perturbation--supply phase voltage V_A, source current i_{sA}, motor currents I_{abc}, speed w_r, developed electromagnetic torque T_e, and DC link voltage.

current can also be compared in Figs. 7-9. It can be observed that the proposed 24-pulse AC-DC converter has input current THD in the range of 2.98% to 4.132% with varying loads. The total magnetic rating is estimated for 12-pulse and 24-pulse AC-DC converters as 26.73% and 41.43% respectively as shown in Table 3. The rating of 24-pulse AC-DC converter is more than that of 12-pulse AC-DC converter due to the increase in the number of windings of main transformers but power quality standard requirements are met without adding any extra diode in the path of load current.

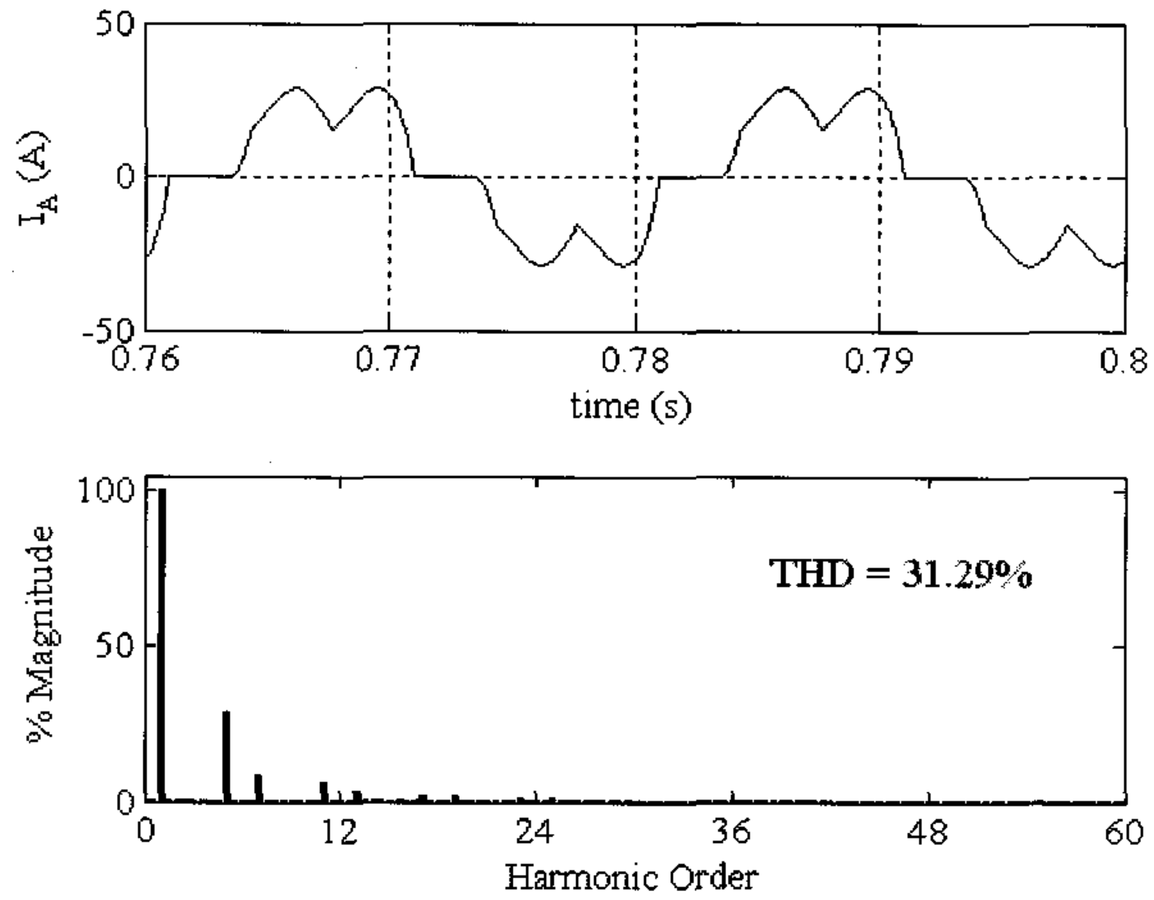

Fig. 7. Input current waveform and harmonic spectrum of 6-pulse AC-DC converter at full-load.

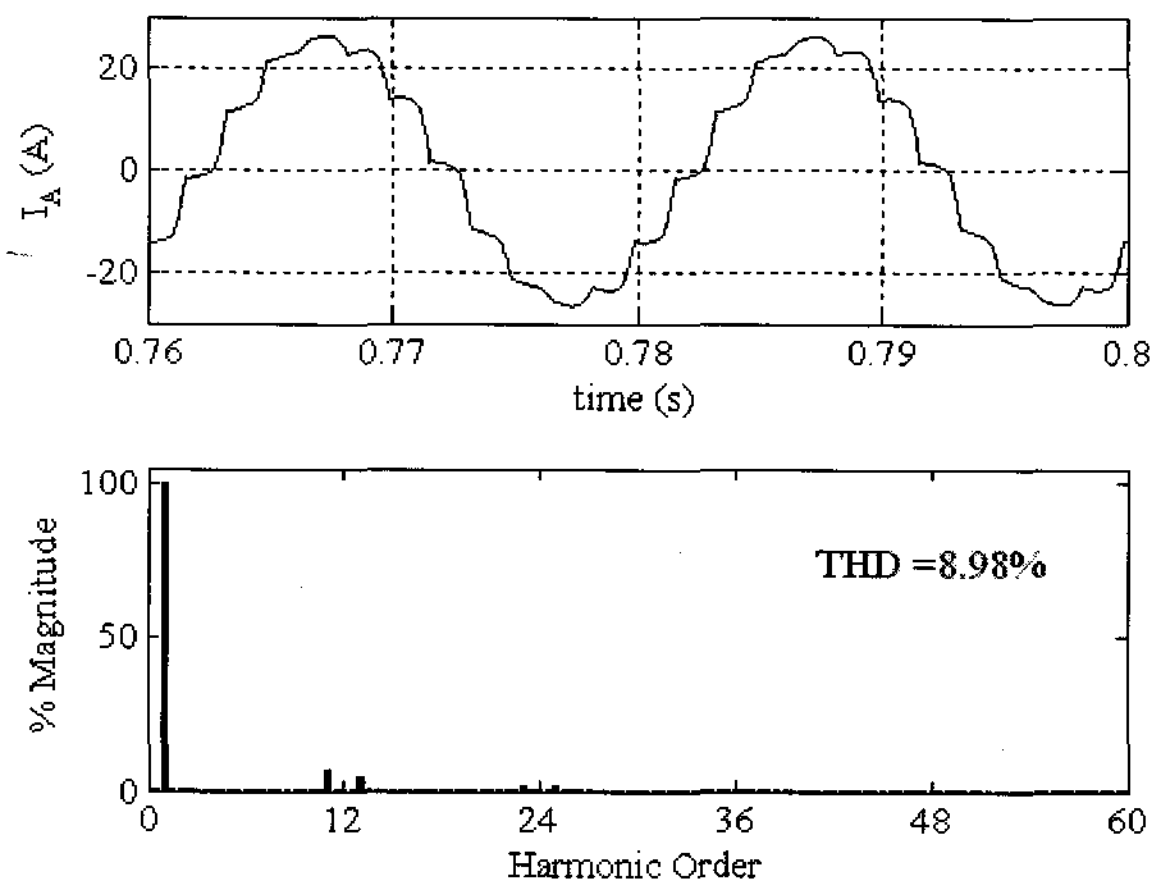

Fig. 8. Input current waveform and harmonic spectrum of 12-pulse AC-DC converter at full-load.

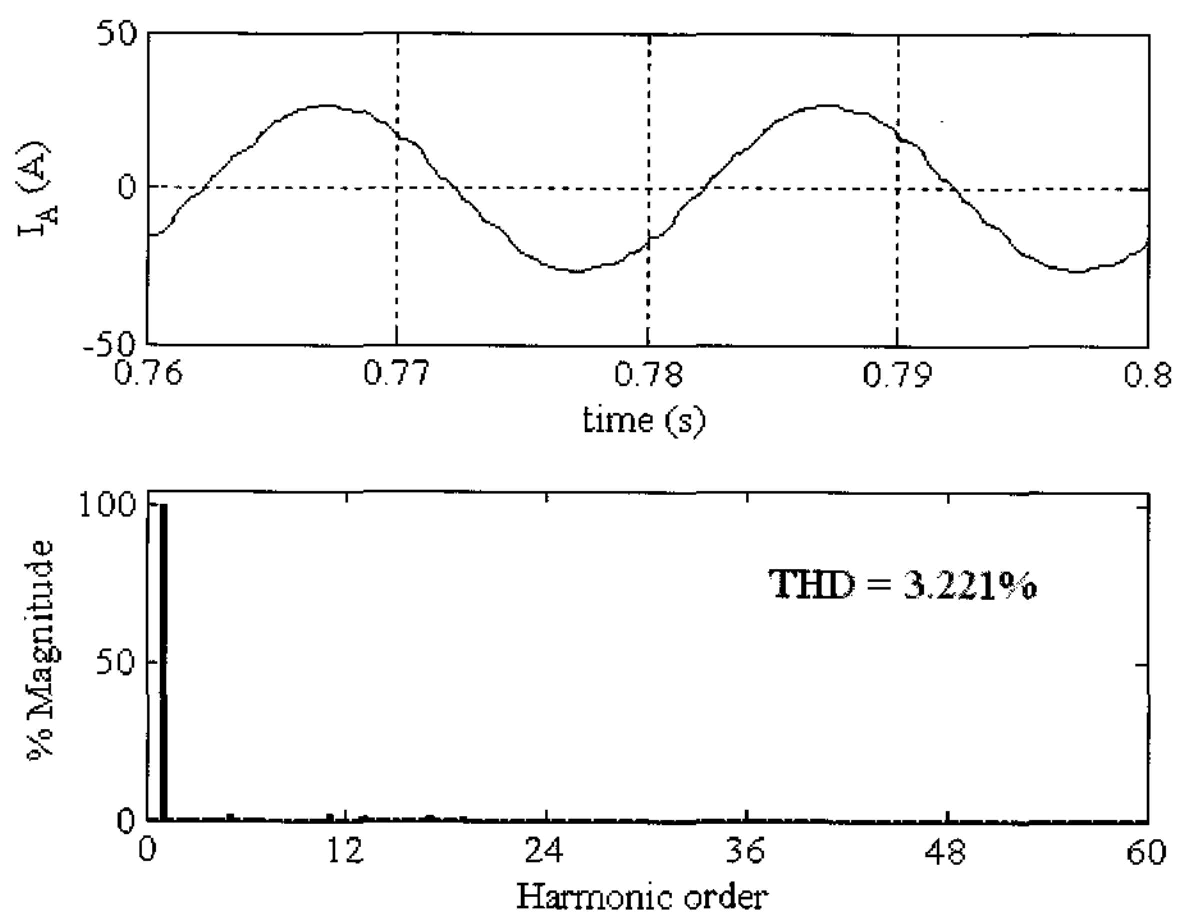

Fig. 9. Input current waveform and harmonic spectrum of 24-pulse AC-DC converter at full-load.

Table 3. Comparison of active-magnetic power ratings in different AC-DC converters.

Sr. No.	Topo-logy	Main Transformer rating (% of load)	Interphase transformer rating (% of load}	Total magnetic rating (% of load)
1	12-pulse	28.68	7.50	36.18
2	24-pulse	49.2	7.36	56.56

Twelve pulse and 24-pulse AC-DC converters are developed in the laboratory and power quality parameters are obtained with equivalent resistive load to validate the design. The design details of developed autotransformers

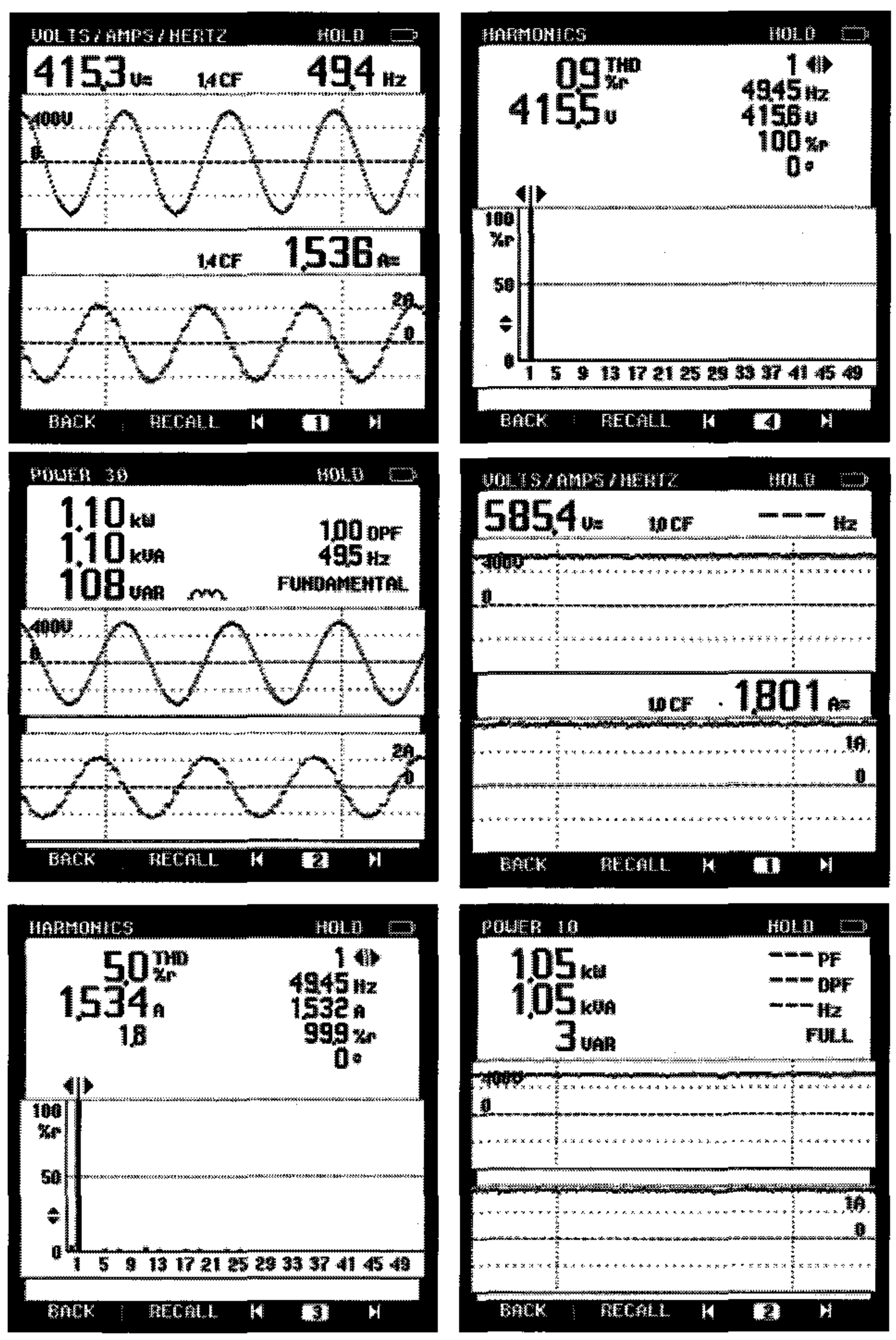

Fig. 10. Test results of 24-pulse AC-DC converter at light load. (a) AC mains voltage and current waveform. (b) Input power, reactive power, and DPF along with supply voltage and current waveform. (c) Harmonic spectrum of AC mains current. (d) Harmonic spectrum of input voltage. (e) DC link voltage and current waveform. (f) DC power along with DC link voltage and current waveform.

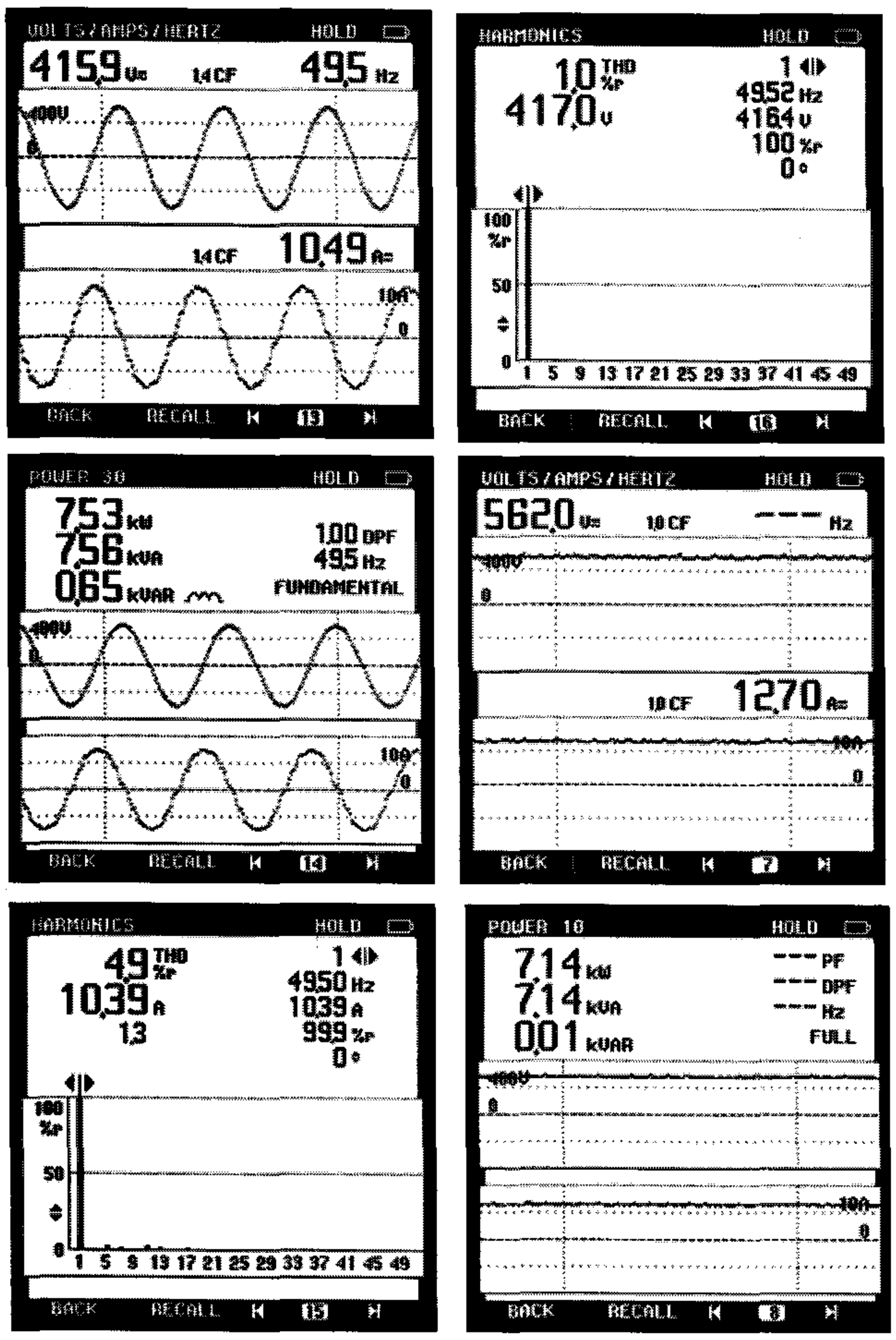

Fig. 11. Test results of 24-pulse AC-DC converter at 7.53kW load. (a) AC mains voltage and current waveform. (b) Input power, reactive power, and DPF along with supply voltage and current waveform. (c) Harmonic spectrum of AC mains current. (d) Harmonic spectrum of input voltage. (e) DC link voltage and current waveform. (f) DC power along with DC link voltage and current waveform.

for 7.5kW, 24-pulse AC-DC converter are given in Appendix. The power quality parameters so obtained are shown in Table 4. The AC mains current waveform and its harmonic spectrum are shown in Fig.10 and 11 for light and full-load respectively. These test results show similar trends as the simulated ones thus validating the design and model of the proposed converter.

5. Conclusions

Based on the proposed design, simulation, and test results, it has been observed that power quality has been improved significantly by employing the proposed zigzag-connected autotransformer based 24-pulse AC-DC converter. The resulting 24-pulse converter has exhibited a high level of performance with clean power characteristics required for diode based front end rectifiers. Simulation and test results have shown that the total harmonic distortion of the input current remains below 8% while power factor remains above 0.99 at varying loads and meets the requirements of IEEE-519 Standards for power quality. The improvement in power quality indices has been observed to be significant in the 24-pulse AC-DC converter.

Table 4. Comparison of power quality parameters of hardware implementation results obtained for 12-pulse and 24-pulse AC-DC converters.

Sr. No.	Topology	Load, (kW)	THD of Vs (%)	AC Mains Current I_s (A)	THD of I_s (%)	Crest Factor, CF	Displacement Factor, DPF	Power Factor, PF	DC Voltage (V)	Load Current I_{dc} (A)
1	12-pulse	0.92	1.1	1.32	15.6	1.4	1.00	0.9985	573.9	1.67
		1.51	1.0	2.12	13.3	1.4	1.00	0.9996	573.0	2.60
		2.17	1.1	3.04	12.1	1.4	1.00	0.9997	570.9	3.77
		3.10	1.1	4.36	11.8	1.4	1.00	0.9997	570.0	5.34
		4.05	1.1	5.68	11.5	1.4	1.00	0.9997	567.4	6.93
		5.18	1.1	7.27	11.2	1.4	1.00	0.9997	566.2	8.84
		5.98	1.1	8.41	11.1	1.4	1.00	0.9997	564.3	10.01
		6.88	1.1	9.63	11.0	1.4	1.00	0.9988	562.4	11.46
		7.64	1.1	10.83	10.7	1.4	1.00	0.9988	561.2	12.24
2	24-pulse	1.10	0.9	1.536	5.0	1.4	1.00	0.9952	584.4	1.801
		2.07	0.8	2.905	4.9	1.4	1.00	0.9962	578.8	3.464
		3.10	0.8	4.352	5.0	1.4	1.00	0.9963	574.8	5.228
		4.20	0.8	5.89	5.0	1.4	1.00	0.9963	572.7	7.07
		5.22	0.8	7.27	5.0	1.4	1.00	0.9963	569.1	8.75
		5.97	0.8	8.36	5.0	1.4	1.00	0.9963	565.8	10.09
		6.53	1.0	9.12	5.0	1.4	1.00	0.9963	564.5	11.02
		6.92	1.0	9.68	5.0	1.4	1.00	0.9963	562.4	11.72
		7.53	1.0	10.49	4.9	1.4	1.00	0.9963	562.0	12.70

Appendix

A. Motor and Controller Specifications:

Three-phase squirrel cage induction motor-
10 hp, 3-phase, 4 pole, Y-connected, 415V, 50Hz.
R_s=0.7384 ohms; R_r = 0.7402 ohms, X_{ls} =0.9561 ohms, X_{lr} = 0.9561 ohms, X_m = 38.96 ohms, J=0.0343 Kgm2
Controller parameters: PI controller K_p= 28; K_i= 100;
DC link filter parameters: L_d = 0.4mH; C_d = 2200μF.

B. Transformer design details:

Flux Density: 0.8Tesla, Current Density: 2.3A/mm2,
Core size: No. 7B
E-Laminations: Length=190mm, Width=124mm
I-Laminations: Length=190mm, Width= 32mm
Area of cross-section of core=48.76cm2(6.40 cm X 7.62cm)

Autotransformer winding details

Winding	Number of turns	Gauge of wire (SWG)
K_1*V_A	241	22
K_2*V_A	108	18
K_3*V_A	4	14
K_4*V_A	32.5	18
K_5*V_A	204.5	22
K_6*V_A	241	22
K_7*V_A	142	20
K_8*V_A	178	20
K_9*V_A	52.5	20
$K_{10}*V_A$	56.5	20

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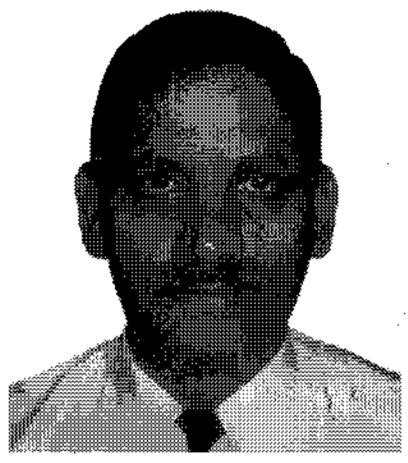

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