Zigzag Autotransformer Based Full-Wave AC-DC Converters

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Abstract – In this paper, a new class of zigzag autotransformer based full-wave AC-DC converters is designed, modeled and simulated to feed non-isolated DC varying loads. The proposed AC-DC converters are suitable in applications such as drives, battery charging, process industries, field excitation systems, etc., where isolation is not essentially required. It is considered as an alternative to the popular bridge configuration having one diode in the path of load current with improved power quality.

Keywords – AC-DC Converters, Power Quality, Zigzag Autotransformer

I. INTRODUCTION

An ANSI 45 configuration of 6-pulse full-wave AC-DC converter shown in Fig. 1, is popularly used for low-voltage and high-current applications that require minimum voltage drop due to source impedance, leakage reactance and in devices used in the path of load current. These full-wave converters generally have star or zigzag secondary. The full-wave rectifiers (not the bridge rectifiers) have only one device in the path of load current and preferred in industrial applications such as electro-chemical, induction heating processes, etc. The six-phase full-wave rectifier of Fig. 1 employs a delta/ double-star transformer (ANSI 45 configuration) and an interphase reactor (IPR). A diode is connected in each output phase for rectification and the technology is well established. Two three-phase output groups are connected so that one is of opposite instantaneous polarity of the other. This mutual disposition of 180° would give six-phase diametric vector if no interphase reactor (IPR) or interphase transformer (IPT) is present and two neutrals are directly connected [1].

It is a usual practice to employ multiple 12-pulse or 18-pulse AC-DC converters fed from such phase–staggered transformers to meet IEEE-519 standard [2] requirements as the total harmonic distortion (THD) of input line currents of single unit is high and may not qualify as clean power at high loads. The isolation transformers used for high currents can have different winding arrangements such as star, delta, fork, zig-zag, polygon etc. The isolation transformers used for full-wave rectifiers have generally delta or star primary winding (sometime polygon winding also) and star or zigzag or fork secondary windings [3-5].

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The star, zigzag and fork windings provide neutral point for full-wave rectifiers, however, two secondary windings have interphase reactors between neutral points as shown in Fig. 1 for full utilization of devices. But a six-phase full-wave AC-DC converter affects the voltage at the point of common coupling (PCC) due to current distortion. Multipulse AC-DC converters are effective in improving power quality where transformers (auto-wound and separately-wound) are employed to generate more phases [6-7] and increase the pulse number in AC-DC converters. ANSI 45 and ANSI 46 transformers are employed together [8] to make the full-wave 12-pulse AC-DC converter. Maslin et. al. [9] have reported a 12-phase full-wave AC-DC converter based on zigzag transformers for electrical induction apparatus. This twelve-pulse converter uses two three-phase transformers having star and delta primary windings but identical zigzag secondary windings [3-5]. This rectifier configuration is reported to use seven interphase reactors. But it is observed that the total harmonic distortion (THD) of input current is not within the IEEE-519 Standard permissible limits in all cases and tuned passive filters are extensively used along with it

ANSI 45 and ANSI 46 rectifier combinations are also described by Brown [10] for copper electro-winning industry. Miyari et. al. [11] have explained a method of pulse multiplication in 6-pulse full-wave rectifiers but it adds one more semiconductor device in the path of load current. An 18-pulse diode bridge based front end AC-DC converter for electrolytic application is explained by Wiechmann et. al. [12]. This topology also have two devices in the path of load current and hence additional voltage drop and losses that is not desired on secondary side as the load current is very large.

The problem with full-wave AC-DC converter in isolated configurations is that the transformer size is nearly 125-145% [5] of the power transferred as only 50% of the windings are effectively used at any instant. But the isolation is very much required in such low-voltage applications for stepping down the voltage and thus these are used extensively. However, full-wave autotransformer based converters that have reduced magnetic rating are not

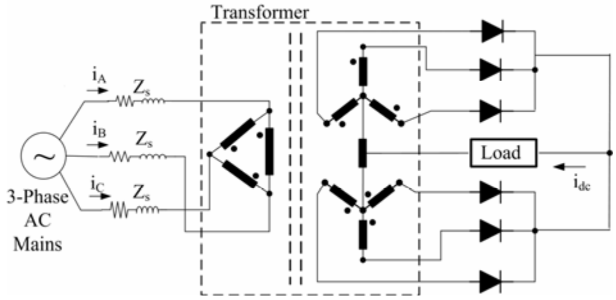

Fig. 1: A 6-phase full-wave AC-DC converter using delta/double-star transformer (ANSI 45 rectifier).

seen in literature.

The non-isolated full-wave AC-DC converters are not known, mainly due to popularity of AC-DC converters employing bridge configurations and the m.m.f. (magneto-motive-force) balance provided by it. However, it is worth noting that the number of devices required in six-pulse AC-DC converter employing full-wave configuration is same as that employed by a six-pulse bridge arrangement, while the forward voltage drop due to the diodes/ thyristors, is reduced. Moreover, the output voltage is reduced to about 57% of that of isolated case. In this paper, a class of non-isolated full-wave AC-DC converters is proposed for applications such as magnet power supplies, battery charging, electrolytic process, motor control, etc. The proposed 6-pulse, 12-pulse, 18-pulse and 24-pulse full-wave AC-DC converters are fed from zigzag-connected autotransformers. Detailed design of the transformer and resulting full-wave diode rectifier systems are carried out to study the behavior of the AC-DC converters. The designed converter systems are modeled and simulated in MATLAB to demonstrate power quality improvement at AC mains. The laboratory prototypes are also developed to validate the design and model of these proposed converters. In higher number of pulse configurations of these converters, power quality at AC mains is improved and qualify IEEE-519 standard requirements.

II. Proposed Full-Wave AC-DC Converter

Fig. 2 shows the proposed 6-pulse full-wave AC-DC converter. In this configuration zigzag connected autotransformer is used. The design is described as follows.

A. Design of Zigzag Autotransformer Suitable for 6-Pulse Full-Wave AC-DC Converter

Fig. 2 shows the schematic of the proposed zigzag connected autotransformer winding arrangement and its connection to two full-wave converters, FW1 and FW2. Two full-wave converters FW1 and FW2 are connected to two sets of three-phases at (A_1, B_1, C_1) and (A_2, B_2, C_2) respectively. Fig. 3 depicts the graphical representation of the autotransformer windings and angular position of various voltage phasors. Two sets of three phase voltages are (V_{A1}, V_{B1}, V_{C1}) and (V_{A2}, V_{B2}, V_{C2}). These sets are displaced by 60° from each other and at +30° and -30° respectively from AC mains voltage V_A. The number of turns for every winding are determined as a function of the phase voltage, V_A(=V). These voltages, as marked in Fig. 3, are expressed by following relationships.

Consider the set of three phase supply voltages as:

$$V_A = V\angle 0°,\ V_B = V\angle -120°, V_C = V\angle 120° \tag{1}$$

$$|V_A| = V_R = 1.1547V_A \tag{2}$$

The required voltages for the converters I (FW1) are:

$$V_{A1} = V_R\angle 30°,\ V_{B1} = V_R\angle -90°, V_{C1} = V_R\angle 150° \tag{3}$$

The required voltages for the converters II (FW2) are:

$$V_{A2} = V_R\angle -30°,\ V_{B2} = V_R\angle -150°, V_{C2} = V_R\angle 90° \tag{4}$$

The values of constants K_1 to K_3 marked in Fig. 3, determine the winding voltages as a fraction of phase windings turns. The value of output voltage phasors can also be expressed in terms of input phase and line voltages as:

$$V_{A1} = K_1V_{AB} - K_1V_{CA} - K_2V_{BC} \tag{5}$$

$$V_{A2} = K_1V_{AB} - K_1V_{CA} + K_2V_{BC} \tag{6}$$

$$V_{C2} = V_C + K_2V_{AB} \tag{7}$$

Eqns. (5-7) give the values of constants K_1 and K_2 for desired phase shift as

$$K_1 = 0.5773,\ K_2 = 0.5773 \tag{8}$$

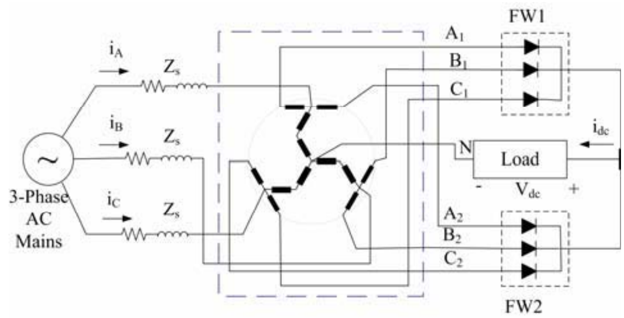

Fig. 2: Proposed zigzag autotransformer based 6-pulse full-wave AC-DC converter.

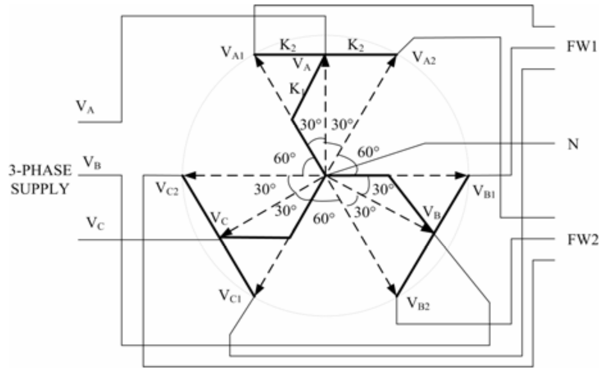

Fig. 3: Winding arrangement and phasor diagram of transformer for 6-pulse non-isolated full-wave AC-DC converter.

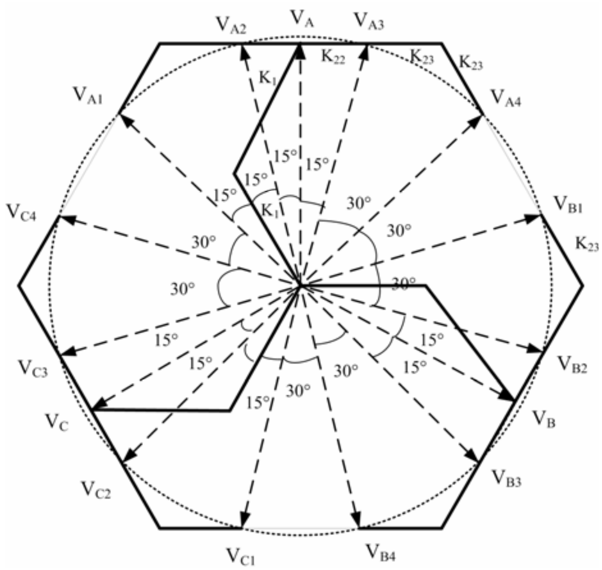

Fig. 4: Winding arrangement and phasor diagram of autotransformer for 12-pulse non-isolated full-wave AC-DC converter converter.

This full-wave converter autotransformer configuration approach has been further modified to get the designs of zigzag autotransformers for 12-pulse, 18-pulse and 24-pulse AC-DC converter configurations. Fig. 4 shows autotransformer winding arrangement for 12-pulse AC-DC converter along with its phasor diagram. The winding arrangement and phasor diagrams for autotransformer employed in 18-pulse and 24-pulse AC-DC converters are shown in Fig. 5a and Fig. 5b respectively. The values of constants (as marked in Figs. 4-5) giving winding voltage as the fraction of input phase voltage for these configurations can be determined in a similar way and these are found as:

12-pulse converter:

K_{22}=0.2699; K_{23}=0.3094; K_{24}=0.5358; (9)

18-pulse converter:

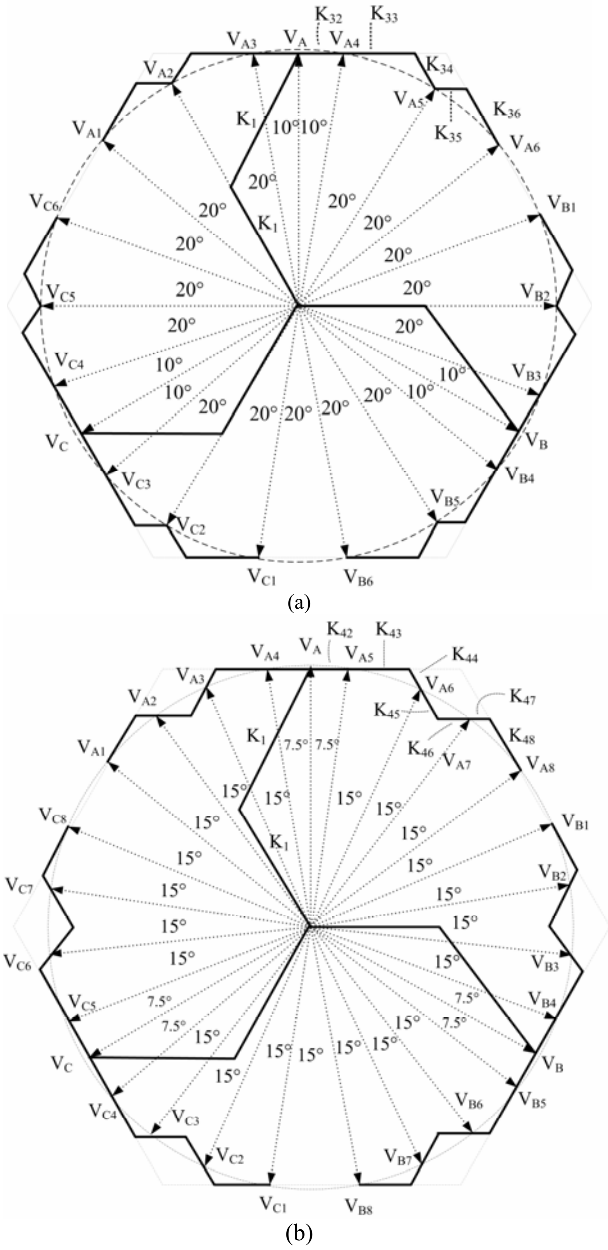

Fig. 5: Winding arrangement and phasor diagram of transformer for (a) 18-pulse and (b) 24-pulse non-isolated full-wave AC-DC converter.

K_{32}=0.1763; K_{33}=0.2577; K_{34}=0.1376; K_{35}=0.1376; K_{36}=0.2577. (10)

24-pulse converter:

K_{42}=0.1316; K_{43}=0.2149; K_{44}=0.0787; K_{45}=0.1520; K_{46}=0.1520; K_{47}=0.0787; K_{48}=0.2149. (11)

The VA rating of these autotransformers is calculated as [6]:

$$\text{VA rating} = 0.5 \sum (V_{winding}\, I_{winding}) \quad (12)$$

III. MATLAB BASED SIMULATION

The proposed 6–pulse, 12-pulse, 18-pulse and 24-pulse non-isolated full-wave AC-DC converters are modeled and simulated in MATLAB environment along with SIMULINK and Power System Blockset (PSB) toolboxes. These full-wave AC-DC converter systems are fed from 415V, 50Hz AC supply. The load connected to the converter is considered of rating of a 5kW, 280V DC load. The value of source impedance used in these simulations is considered a practical value of 3%. The specifications of these converters are given in Appendix. Fig. 6 shows the MATLAB model of the 12-pulse full-wave AC-DC converter to improve various power-quality indices and Fig. 7 shows the model of the autotransformer winding arrangement used. The simulations of the 6-pulse, 18-pulse and 24-pulse full-wave AC-DC converters are also carried out in similar way for same supply and load conditions for comparing their performance.

IV. RESULTS AND DISCUSSION

The power quality indices obtained from simulations of 6-pulse, 12-pulse, 18-pulse and 24-pulse AC-DC converters at varying load are given in Table 1 The waveforms of input current along with supply voltage and output DC voltage and current are shown in Figs. 8-11.

Fig. 8: (a) shows the input AC waveforms with the output DC voltage and current waveforms of six-pulse converter configuration. The current is highly non-sinusoidal and the (6k±1) harmonics are prevalent which can be seen in Fig. 8(b) that shows input current waveform and its harmonic spectrum. The total harmonic distortion (THD) of AC mains current at full-load for this six-pulse converter is observed to be 25.9% which is much away

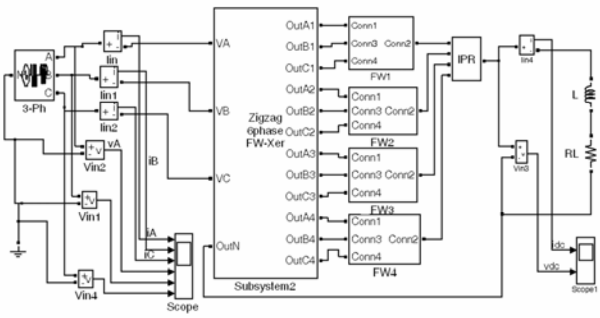

Fig. 6: MATLAB model of the 12-pulse full-wave AC-DC converter employing zigzag-autotransformer.

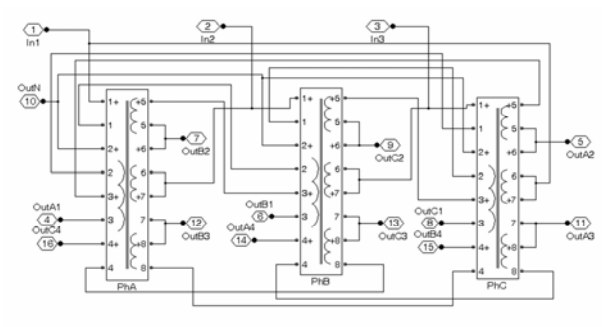

Fig. 7: MATLAB model of the proposed zigzag-Autotransformer for 12-pulse full-wave AC-DC converter.

from power quality standard (IEEE-519) requirements of 8%, like the other six-pulse AC-DC converters. However, it may be useful if it used with a passive or active filter to meet power quality requirement.

Fig. 9(b) shows the input current waveform and its harmonic spectrum for 12-pulse AC-DC converter. The THD of AC mains current is observed to be 10.96% and it has dominant 11th and 13th harmonics. Fig. 10(a) shows the input current waveform along with the supply phase voltage for 18-pulse AC-DC converter and 18-steps in a cycle can be clearly seen in these current waveforms. The input current has become close to sinusoidal and power factor (PF) has also improved. Moreover, the output DC

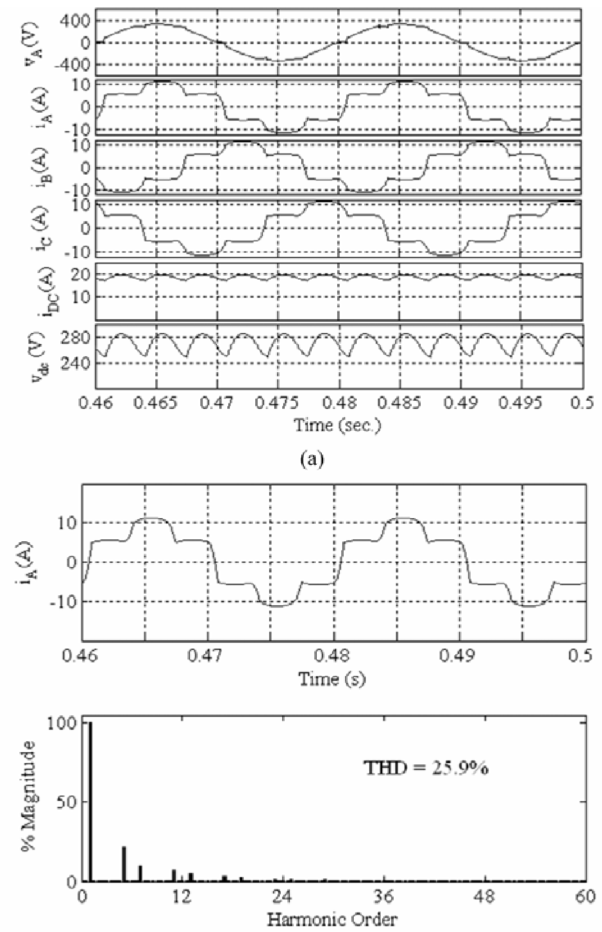

Fig. 8: Six-pulse full-wave AC-DC converter at full-load - (a) Input and output voltage and current waveform (b) Input current waveform and its harmonic spectrum.

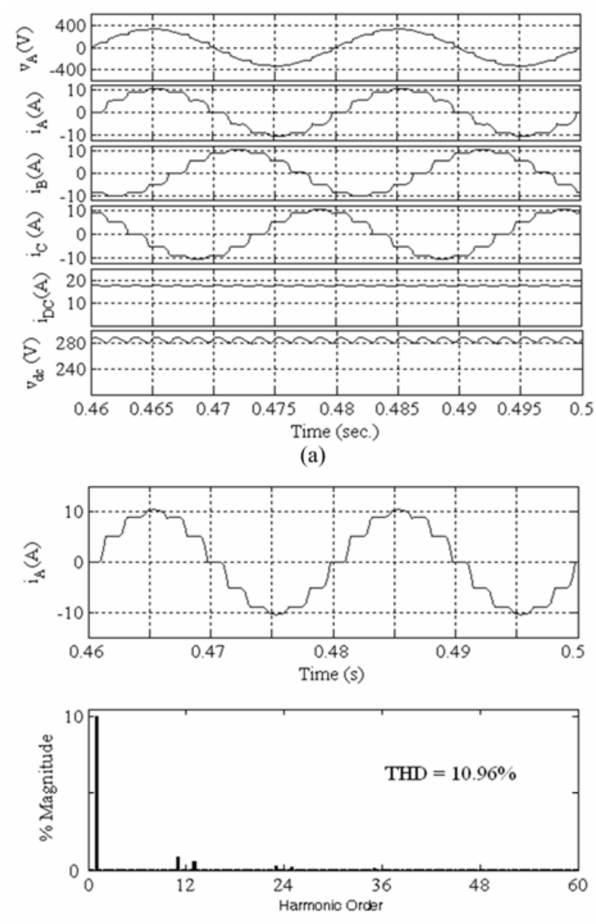

Fig. 9: Twelve-pulse full-wave AC-DC converter at full-load - (a) Input and output voltage and current waveform (b) Input current waveform and its harmonic spectrum.

voltage has 18 ripples of low peak-to-peak value. The THD of AC mains current is observed to be 6.01% at full-load as shown in Fig. 10(b). Table 1 shows that the value of THD varies in range 6.01% to 6.55% with varying load for this converter configuration and it meets IEEE-519 Standard requirements of power quality.

Fig. 11(a) shows the input voltage and current waveforms along with output DC voltage and current waveforms of 24-pulse AC-DC converter. The waveforms of input current as well as output voltage has improved remarkably without employing any filter at front end. The input AC mains current waveform is almost sinusoidal and has dominant 23rd and 25th harmonics as shown in Fig. 11(b). Table 1 depicts that the THD variation of input current is 4.6% to 5.8% with the load and power factor is observed of order of 0.99.

The variation of THD of AC mains current and power factor with the load for these 6-pulse, 12-pulse, 18-pulse and 24-pulse full-wave non-isolated converter configurations are shown in Figs. 12 and 13 respectively. It clearly shows a remarkable improvement in power quality in the case of 24-pulse AC-DC converter.

Table 1 Comparison of power quality parameters of the different full-wave AC-DC converters

Sr. No.	Topo-logy	% Load	%THD of V_A	AC Mains Current I_A (A)	% THD of I_A,	Distortion Factor	Displace-ment Factor	Power Factor	DC Voltage V_{dc}(V)	Load Current I_{dc} (A)	Ripple Factor %
1	6-pulse	20	1.982	1.587	28.19	0.9623	0.9973	0.9597	278.4	3.819	4.622
		40	3.265	3.111	27.6	0.9634	0.9953	0.9589	276.6	7.588	4.728
		60	4.379	4.609	27.0	0.9645	0.9934	0.9581	274.8	11.31	4.673
		80	5.359	6.08	26.44	0.9645	0.9915	0.9572	272.9	14.98	4.51
		100	6.274	7.529	25.9	0.9660	0.9898	0.9562	271.2	18.6	4.29
2	12-pulse	20	1.623	1.515	12.58	0.9921	0.9977	0.9898	289.1	3.559	1.221
		40	2.668	2.951	12.23	0.9922	0.9975	0.9898	288.1	7.094	1.248
		60	3.541	4.375	11.79	0.9925	0.9968	0.9893	287.1	10.6	1.20
		80	4.304	5.788	11.36	0.9927	0.9960	0.9887	286.1	14.09	1.12
		100	4.997	7.189	10.96	0.9928	0.9954	0.9882	285.2	17.55	1.031
3	18-pulse	20	1.303	1.558	6.522	0.9978	0.9910	0.9889	283.4	3.615	0.5575
		40	2.168	2.976	6.50	0.9977	0.9911	0.9888	282.5	7.205	0.5275
		60	2.902	4.39	6.384	0.9975	0.9933	0.9908	281.6	10.78	0.4655
		80	3.552	5.795	6.21	0.9974	0.9941	0.9915	280.8	14.32	0.4047
		100	4.123	7.192	6.015	0.9974	0.9944	0.9918	279.9	17.85	0.3538
4	24-pulse	20	1.363	1.531	5.797	0.9982	0.9991	0.9974	282.2	3.344	0.3344
		40	2.199	2.944	5.504	0.9982	0.9939	0.9989	281.8	7.189	0.3429
		60	2.875	4.352	5.176	0.9983	0.9987	0.9969	281.4	10.77	0.3245
		80	3.457	5.756	4.872	0.9982	0.9985	0.9967	281.0	14.34	0.2971
		100	3.97	7.155	4.593	0.9982	0.9984	0.9965	280.6	17.89	0.2694

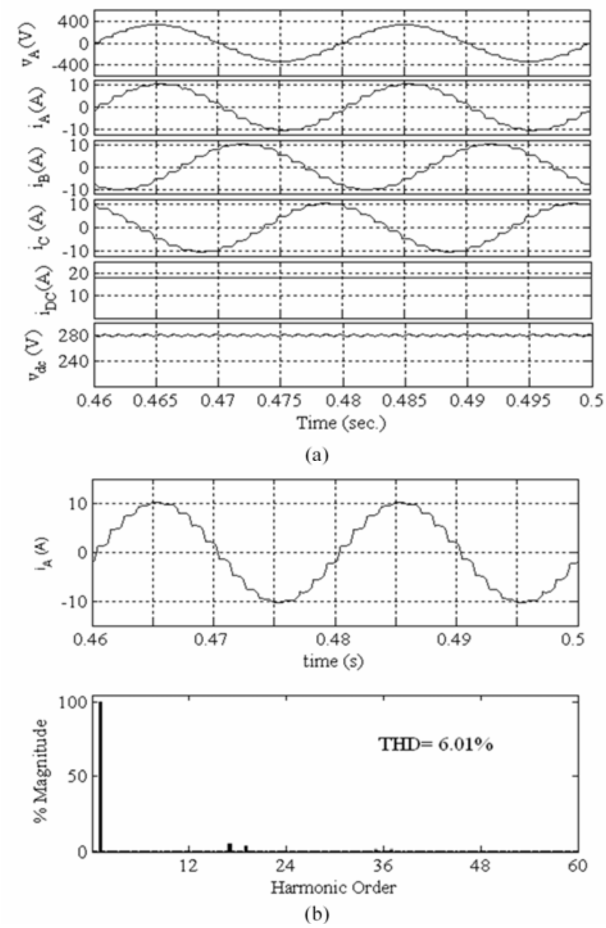

Fig. 10: Eighteen-pulse full-wave AC-DC converter at full-load - (a) Input and output voltage and current waveform (b) Input current waveform and its harmonic spectrum.

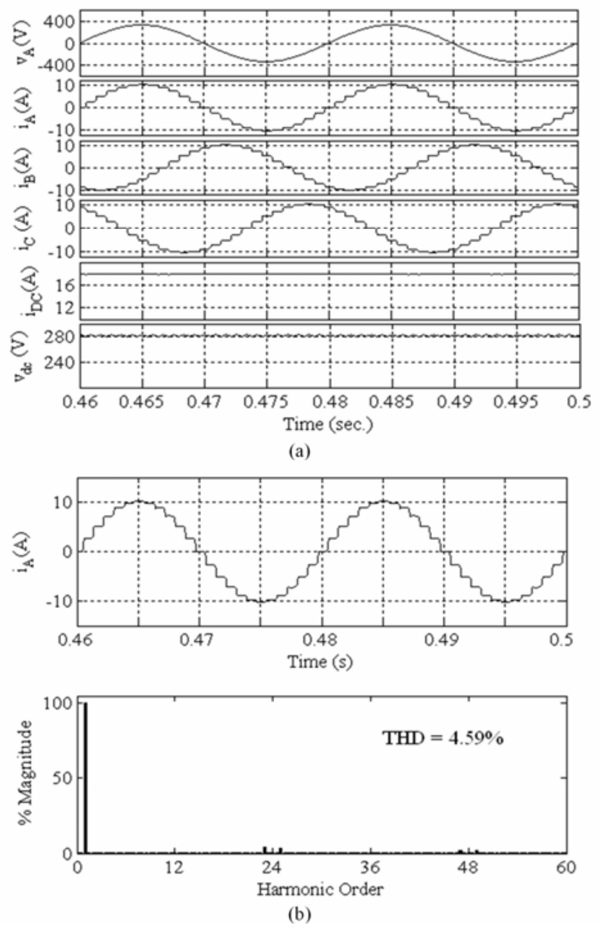

Fig. 11: Twenty four-pulse full-wave AC-DC converter at full load – (a) Input and output voltage and current waveform (b) Input current waveform and its harmonic spectrum.

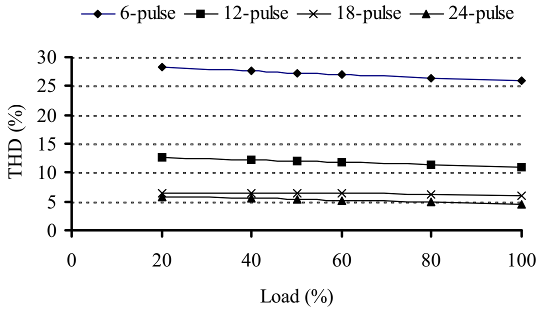

Fig. 12: Variation of input current total harmonic distortion with load.

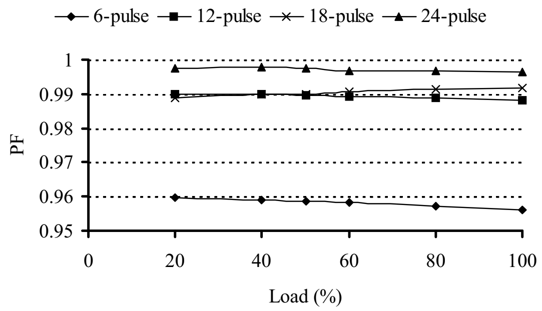

Fig. 13: Variation of power factor with load

The rating of these autotransformers for 6, 12, 18 and 24-pulse AC-DC converter configurations is estimated as 86.8%, 107.6%, 93.5% and 92.8% of the DC load rating respectively, which is much less than that of isolated topologies of full-wave AC-DC converters.

V. Experimental Validation

To validate the design and modeling of these converters, a non-isolated full-wave 12-pulse AC-DC converter is developed in the laboratory for 7.5kW, 270V DC load. The same converter autotransformer is also employed for validating 6-pulse AC-DC converter configuration. The autotransformer design details of this developed autotransformer are given in Appendix. The number of turns and gauge of wire used for developed prototype are also given. Extensive tests are conducted on the prototype at varying loads and the power quality indices are recorded using power analyzer. The results for varying loads are given in Table 2. These recorded waveforms at full-load for 6-pulse and 12-pulse AC-DC converter configurations are shown in Figs. 14 and 15 respectively. The variation of THD of input current in simulation results in 6-pulse AC-DC converter is 25.9% to 28.19% similar to test results having input current THD variation in range of 27.0% to 28.3%. Similarly, in 12-pulse full-wave AC-DC converter the input current THD is observed from simulation and test results to vary from 10.96% to 12.58% and 11.3 to 12.6%, respectively. These hardware results are in line with the simulation results of these converters and validate the proposed design and model of this new class of full-wave non-isolated AC-DC converters.

The zigzag autotransformers used for these 6, 12, 18 and 24-pulse full-wave AC-DC converter systems have

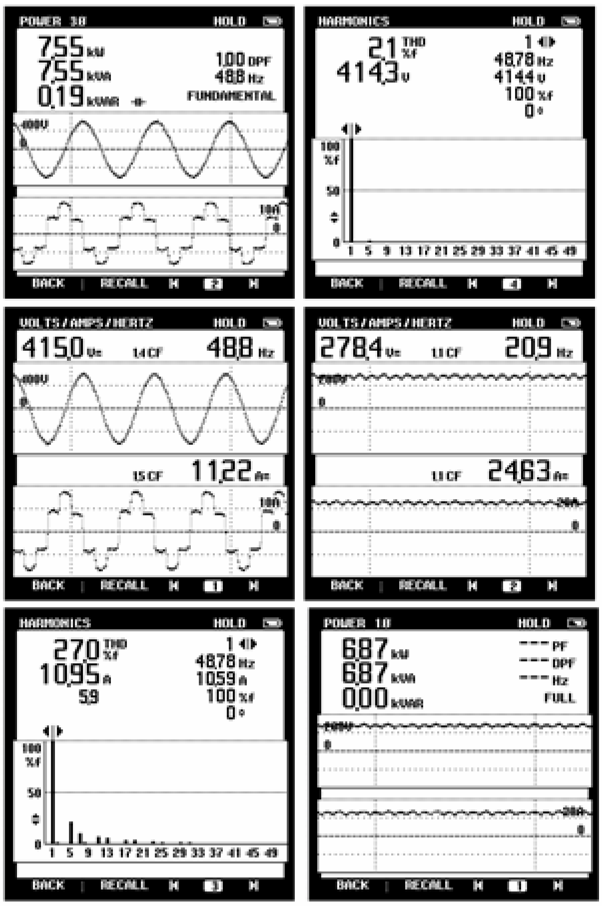

Fig. 14: Test results showing input and output waveforms and harmonic spectrum of input current/ voltage waveforms of proposed six-pulse AC-DC converter at full-load.

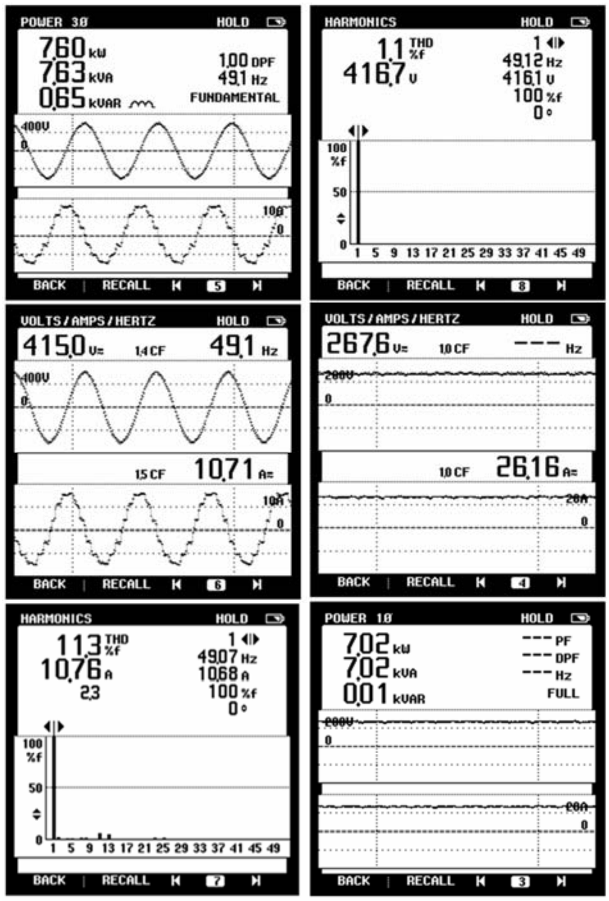

Fig. 15: Test results showing input and output waveforms and harmonic spectrum of input current/ voltage waveforms of proposed twelve-pulse AC-DC converter at full-load.

provided balanced outputs voltages for rectification and low voltage applications. Obtained results have demonstrated that the proposed 18 and 24-pulse full-wave AC-DC converters exhibit a high level performance with clean power characteristics.

The total harmonic distortion of input current is observed to be less than 8% at varying loads and meets IEEE-519 Standard power quality requirements. The output voltage ripple is of order less than 0.4% and input power factor is improved at varying loads thereby improving power quality at AC mains and output load.

Table 2 Test results for Comparison of power quality parameters of different AC-DC converters

Topology	Input Power (kW)	%THD of V_A	AC Mains Current I_A (A)	% THD of I_A,	Power Factor	DC Voltage (V_{dc})	Load Current I_{dc} (A)
6-pulse	1.13	2.0	1.64	28.3	0.9585	318.7	3.21
	1.95	2.0	2.85	27.9	0.9535	311.2	6.15
	4.01	2.0	6.09	27.4	0.9160	298.9	12.91
	5.91	1.8	8.79	27.3	0.9349	283.5	19.61
	7.55	2.1	11.22	27.0	0.9361	278.4	24.63
12-pulse	1.07	1.0	1.52	12.6	0.9793	296.7	3.51
	2.06	1.1	2.93	12.5	0.9781	290.5	6.95
	3.18	1.2	4.47	12.3	0.9897	285.8	10.98
	4.04	1.2	5.73	12.0	0.9808	280.1	14.07
	6.00	1.2	8.40	11.4	0.9878	275.7	20.56
	7.60	1.1	10.71	11.3	0.9872	267.6	26.16

VI. Conclusion

The zigzag autotransformers used for these 6, 12, 18 and 24-pulse full-wave AC-DC converter systems have formed a new class of AC-DC converters. These converters provide balanced outputs voltages for rectification and suits for lower secondary voltage applications. Obtained results have demonstrated that the proposed 18 and 24-pulse full-wave AC-DC converters exhibit a high level performance with clean power characteristics. The total harmonic distortion of input current is observed to be less than 8% at varying loads and meets IEEE-519 Standard power quality requirements. The output voltage ripple is of order less than 0.4% and input power factor is improved at varying loads thereby improving power quality at AC mains and output load.

Appendix

Converter Specifications:

AC Supply: 415V, 50Hz.

Source impedance: Z_s= j1.036ohms (=3%)

DC Load: 5kW, 280 V DC, L_{dc} =0.1mH

Transformer design details:

Flux Density: 0.8Tesla, Current Density: 2.3A/mm^2,

Core size: No. 7B

E-Laminations: Length=190mm, Width=124mm

I-Laminations: Length=190mm, Width= 32mm

Area of cross-section of core=48.76cm^2(6.40 cm X 7.62cm)

Autotransformer winding details-

Winding Number of turns Gauge of wire (SWG)

Winding	Number of	Gauge of wire
K_1*V_A	155	18
K_{22} *V_A	72	18
K_{23}* V_A	83	20
K_{24} *V_A	144	24

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