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88-Pulse AC-DC Converter for Power Quality Improvement

Rohollah Abdollahi
Qom Branch, Islamic Azad University, Qom, Iran
(Rohollah.abdollahi@yahoo.com)

Abstract-This paper presents a pulse doubling technique in a 44-pulse ac-dc converter which supplies direct torque controlled motor drives (DTCIMD's) in order to have better power quality conditions at the point of common coupling. The proposed technique increases the number of rectification pulses without significant changes in the installations and yields in harmonic reduction in both ac and dc sides. The 44-pulse rectified output voltage is accomplished via two paralleled 22-pulse ac-dc converters each of them consisting of 11-phase diode bridge rectifier. An autotransformer is designed to supply the rectifiers. The design procedure of magnetics is in a way such that makes it suitable for retrofit applications where a six-pulse diode bridge rectifier is being utilized. Independent operation of paralleled diode-bridge rectifiers, i.e. dc-ripple re-injection methodology, requires a Zero Sequence Blocking Transformer (ZSBT). Finally, a tapped interphase reactor is connected at the output of ZSBT to double the pulse numbers of output voltage up to 88 pulses. The aforementioned structure improves power quality criteria at ac mains and makes them consistent with the IEEE-519 standard requirements for varying loads. Furthermore, near unity power factor is obtained for a wide range of DTCIMD operation. A comparison is made between 6-pulse, 44-pulse, and proposed converters from view point of power quality indices. Results show that input current total harmonic distortion (THD) is less than 2% for the proposed topology at variable loads.

Keywords- *AC–DC converter, polygon autotransformer, power quality, 88-pulse, Pulse Doubling, direct torque controlled induction motor drive (DTCIMD).*

I. INTRODUCTION

Recent advances in solid state conversion technology has led to the proliferation of variable frequency induction motor drives (VFIMD's) that are used in several applications such as air conditioning, blowers, fans, pumps for waste water treatment plants, textile mills, rolling mills etc [1]. The most practical technique in VFIMD's is direct torque controlled strategy in that it offers better performance rather than the other control techniques. Direct torque controlled technique is implemented in voltage source inverter which is mostly fed from six-pulse diode bridge rectifier, Insulated gate bipolar transistors (IGBT's) are employed as the VSI switches. The most important drawback of the six-pulse diode-bridge rectifier is its poor power factor injection of current harmonics into ac mains. The circulation of current harmonics into the source impedance yields in harmonic polluted voltages at the point of common coupling (PCC) and consequently resulting in undesired supply voltage conditions for costumers in the vicinity. The value of current harmonic components which are injected into the grid by nonlinear loads such as DTCIMDs should be confined within the standard limitations. The most prominent standards in this field are IEEE standard 519 [2] and the International Electro technical Commission (IEC) 61000-3-2 [3].

According to considerable growth of Static Power Converters (SPC's) that are the major sources of harmonic distortion and as a result their power quality problems, researchers have focused their attention on harmonic eliminating solutions. For DTCIMD's one effective solution is to employ multi pulse AC-DC converters. These converters are based on either phase multiplication or phase shifting or pulse doubling or a combination [4]-[25]. Although, in the conditions of light load or small source impedance, line current total harmonic distortion (THD) will be more than 3% for up to 24-pulse AC-DC converters. Accordingly, 30-pulse autotransformer based AC-DC converter and 36-pulse configuration have been presented in [22] and [23], respectively. Current THD varies between 2.63% and 3.71% (for light loads) for the first and between 2.038% and 3.748% for the second schematics. Obviously, THD is not satisfactory in light load conditions for these two AC-DC converters. Afterwards, 38-pulse and a 40-pulse based autotransformer converters are reported in [24] and [25], respectively. The 38-pulse converter was adopted for keeping US navy requirement of input THD below 3%, and the 40-pulse one was designed for VCIMD's which has THD variation of 2.226% to 3.851% from full-load to light-load (20% of full-load) respectively.

In this paper, an 88-pulse ac-dc converter is extracted from a 44-pulse ac-dc converter through adding a pulse doubling circuit in the DC link. The proposed design method will be suitable even when the transformer output voltages vary while keeping its 44-pulse operation. In the proposed structure, two 11-leg diode-bridge rectifiers are paralleled via a Zero Sequence Blocking Transformer (ZSBT) and fed from an autotransformer. Hence, a 44-pulse output voltage is obtained. In order to double the number of pulses up to 88, a tapped Inter-Phase Reactor (IPR) with two additional diodes are included in the rectifiers output. This pulse multiplication works on the basis of ripple re-injection method, where the power of the circulating ripple frequency is fed back to the dc system via an IPR [28].

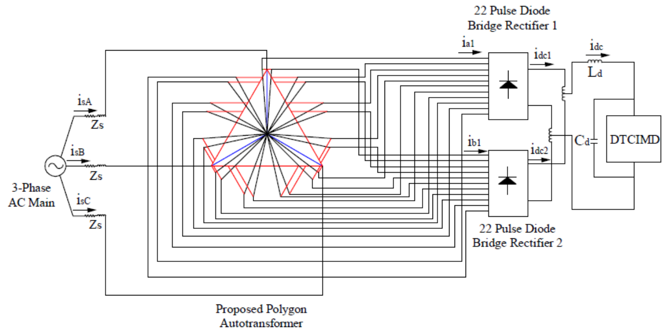

Fig. 1. Polygon-autotransformer configuration for 44-pulse ac–dc conversion.

Furthermore, a 44-pulse ac-dc converter consisting of a polygon autotransformer, two 22-pulse diode bridge rectifiers paralleled through two IPTs, and with a DTCIMD load Fig. 1 is also designed and simulated to compare its operation with the proposed 88-pulse ac-dc converter. Simulation results of six-pulse, 44-pulse and proposed 88-pulse ac-dc converters feeding a DTCIMD load are scheduled and various quality criteria such as THD of ac mains current, power factor, displacement factor, distortion factor, and THD of the supply voltage at PCC are compared.

II. PROPOSED 88-PULSE AC–DC CONVERTER

As mentioned previously, the pulse-doubling technique requires a zero-sequence-blocking transformer (ZSBT) and a diode-tapped inter-phase reactor to multiple the number of a pulses up to 88.It is known that a 12-pulse rectified voltage can be made with two paralleled six-pulse three-phase (three-leg) diode-bridge rectifiers. The phase shift between two supplying voltages should be 30 degrees. Similarly, in order to implement a 44-pulse ac-dc converter through paralleling two bridge rectifiers, i.e. two 22-pulse rectifiers, two sets of 11-phase voltages with a phase difference of 32.72 degrees between the voltages of each group and 8.18 degrees between the same voltages of the two groups are required.

Accordingly, each bridge rectifier consists of 11 common-anode and 11 common-cathode diodes (two 11-leg rectifiers). Autotransformer connections and its phasor diagram which shows the angular displacement of voltages are illustrated in Fig. 2.

A. *Design of Proposed Autotransformer for 44-Pulse AC–DC Converter*

The aforementioned two voltage sets are called as (V_{a1}, V_{a2}, V_{a3}, V_{a4}, V_{a5}, V_{a6}, V_{a7}, V_{a8}, V_{a9}, V_{a10}, V_{a11}) and (V_{b1}, V_{b2}, V_{b3}, V_{b4}, V_{b5}, V_{b6}, V_{b7}, V_{b8}, V_{b9}, V_{b10}, V_{b11}) that are fed to rectifiers I and II, respectively. The same voltages of the two groups, i.e. V_{ai} and V_{bi}, are phase displaced of 8.18 degrees. V_{a1} and V_{b1} has a phase shift of +4.09 and -4.09 degrees from the input voltage of phase A, respectively. According to phasor diagram, the 11-phase voltages are made from ac main phase and line voltages with fractions of the primary winding turns which are expressed with the following relationships. Consider three-phase voltages of primary windings as follows:

$$V_A = V_s\angle 0^\circ,\ V_B = V_s\angle -120^\circ,\ V_C = V_s\angle 120^\circ. \quad (1)$$

Where, 11-phase voltages are:

$$\begin{aligned} &V_{a1} = V_s\angle +4.09^\circ, V_{a2} = V_s\angle -28.637^\circ, V_{a3} = V_s\angle -61.364^\circ,\\ &V_{a4} = V_s\angle -94.091^\circ, V_{a5} = V_s\angle -126.818^\circ, V_{a6} = V_s\angle -159.545^\circ,\\ &V_{a7} = V_s\angle -192.272^\circ, V_{a8} = V_s\angle -224.999^\circ, V_{a9} = V_s\angle -257.726^\circ,\\ &V_{a10} = V_s\angle -290.453^\circ, V_{a11} = V_s\angle -323.18^\circ. \end{aligned} \quad (2)$$

$$\begin{aligned} &V_{b1} = V_s\angle -4.09^\circ, V_{b2} = V_s\angle -36.817^\circ, V_{b3} = V_s\angle -69.544^\circ,\\ &V_{b4} = V_s\angle -102.271^\circ, V_{b5} = V_s\angle -134.998^\circ, V_{b6} = V_s\angle -167.725^\circ,\\ &V_{b7} = V_s\angle -200.452^\circ, V_{b8} = V_s\angle -233.179^\circ, V_{b9} = V_s\angle -265.906^\circ,\\ &V_{b10} = V_s\angle -298.633^\circ, V_{b11} = V_s\angle -331.36^\circ. \end{aligned} \quad (3)$$

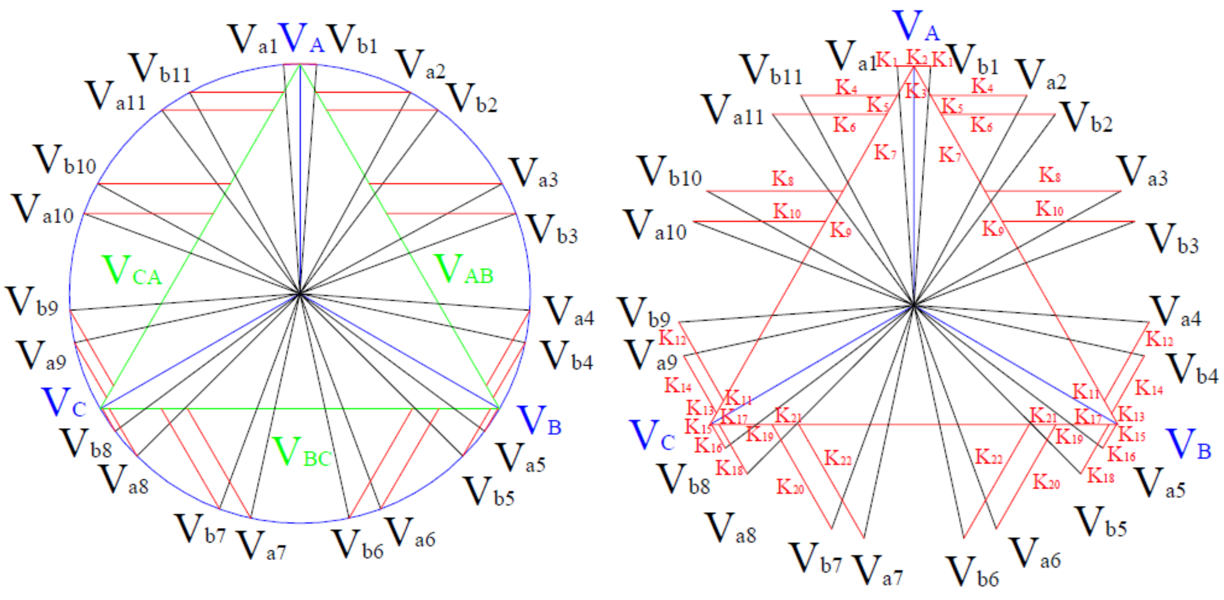

Fig.2. Polygon connection of proposed autotransformer for 44-pulse converter and its phasor representation.

$$\begin{aligned}
V_{a1} &= V_A + K_1 V_{CA} - K_2 V_{BC} \\
V_{a2} &= V_A - K_3 V_{AB} + K_4 V_{BC} \\
V_{a3} &= V_A - K_7 V_{AB} + K_8 V_{BC} \\
V_{a4} &= V_B + K_{11} V_{AB} - K_{12} V_{CA} \\
V_{a5} &= V_B - K_{15} V_{BC} + K_{16} V_{CA} \\
V_{a6} &= V_B - K_{19} V_{BC} + K_{20} V_{CA} \\
V_{a7} &= V_C + K_{21} V_{BC} - K_{22} V_{AB} \\
V_{a8} &= V_C + K_{17} V_{BC} - K_{18} V_{AB} \\
V_{a9} &= V_C - K_{13} V_{CA} + K_{14} V_{AB} \\
V_{a10} &= V_A + K_9 V_{CA} - K_{10} V_{BC} \\
V_{a11} &= V_A + K_5 V_{CA} - K_6 V_{BC}
\end{aligned} \tag{4}$$

Input voltages for converter II are:

$$\begin{aligned}
V_{b1} &= V_A - K_1 V_{AB} + K_2 V_{BC} \\
V_{b2} &= V_A - K_5 V_{AB} + K_6 V_{BC} \\
V_{b3} &= V_A - K_9 V_{AB} + K_{10} V_{BC} \\
V_{b4} &= V_B + K_{13} V_{AB} - K_{14} V_{CA} \\
V_{b5} &= V_B - K_{17} V_{BC} + K_{18} V_{CA} \\
V_{b6} &= V_B - K_{121} V_{BC} + K_{22} V_{CA} \\
V_{b7} &= V_C + K_{19} V_{BC} - K_{20} V_{AB} \\
V_{b8} &= V_C + K_{15} V_{BC} - K_{16} V_{AB} \\
V_{b9} &= V_C - K_{11} V_{CA} + K_{12} V_{AB} \\
V_{b10} &= V_A + K_7 V_{CA} - K_8 V_{BC} \\
V_{b11} &= V_A + K_3 V_{CA} - K_4 V_{BC}
\end{aligned} \tag{5}$$

$$V_{AB} = \sqrt{3} V_A \angle 30^\circ, V_{BC} = \sqrt{3} V_B \angle 30^\circ, V_{CA} = \sqrt{3} V_C \angle 30^\circ. \tag{6}$$

Constants K_1-K_{22} are calculated using (2)-(6) to obtain the required windings turn numbers to have the desired phase shift for the two voltage sets:

$$\begin{aligned}
&K_1 = 0.0017, K_2 = 0.04032, K_3 = 0.08155, K_4 = 0.23592, \\
&K_5 = 0.13296, K_6 = 0.27951, K_7 = 0.34717, K_8 = 0.33315, \\
&K_9 = 0.43368, K_{10} = 0.32412, K_{11} = 0.06699, K_{12} = 0.21878, \\
&K_{13} = 0.031656, K_{14} = 0.15999, K_{15} = 0.0047, K_{16} = 0.06618, \\
&K_{17} = 0.022701, K_{18} = 0.13805, K_{19} = 0.15258, K_{20} = 0.29129, \\
&K_{21} = 0.21821, K_{22} = 0.31808.
\end{aligned} \tag{7}$$

B. Design of Autotransformer for Retrofit Applications

The value of output voltage in multipulse rectifiers boosts relative to the output voltage of a six-pulse converter making the multipulse rectifier inappropriate for retrofit applications. For instance, with the autotransformer arrangement of the proposed 88-pulse converter, the rectified output voltage is 20% higher than that of six-pulse rectifier. For retrofit applications, the above design procedure is modified so that the dc-link voltage becomes equal to that of six-pulse rectifier. This will be accomplished via modifications in the tapping positions on the windings as shown in Fig. 3. It should be noted that with this approach, the desired phase shift is still unchanged. Similar to section II part A, the following equations can be derived as:

$$|V_S| = 0.828|V_A| \tag{8}$$

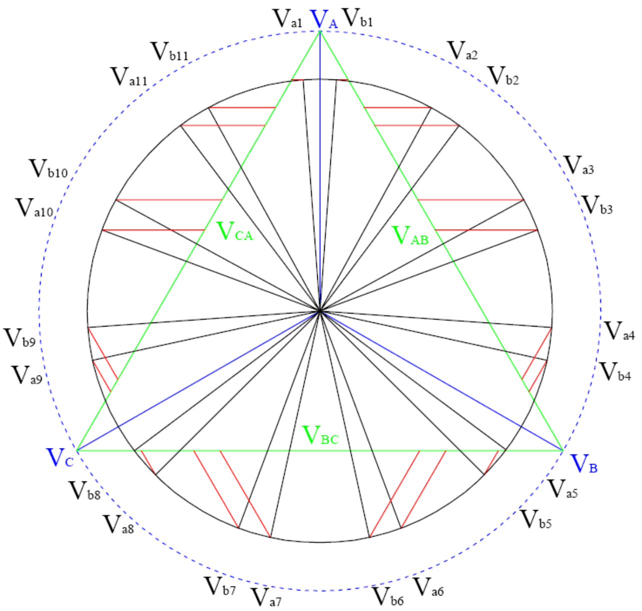

Fig.3. Phasor diagram of voltages in the proposed autotransformer connection along with modifications for retrofit arrangement.

Input voltages for converter I are:

$$\begin{aligned}
V_{a1} &= V_A + K_1 V_{CA} + K_2 V_{BC} \\
V_{a2} &= V_A - K_3 V_{AB} + K_4 V_{BC} \\
V_{a3} &= V_A - K_7 V_{AB} + K_8 V_{BC} \\
V_{a4} &= V_B + K_{11} V_{AB} - K_{12} V_{CA} \\
V_{a5} &= V_B - K_{15} V_{BC} - K_{16} V_{CA} \\
V_{a6} &= V_B - K_{19} V_{BC} + K_{20} V_{CA} \\
V_{a7} &= V_C + K_{21} V_{BC} - K_{22} V_{AB} \\
V_{a8} &= V_C + K_{17} V_{BC} - K_{18} V_{AB} \\
V_{a9} &= V_C - K_{13} V_{CA} + K_{14} V_{AB} \\
V_{a10} &= V_A + K_9 V_{CA} - K_{10} V_{BC} \\
V_{a11} &= V_A + K_5 V_{CA} - K_6 V_{BC}
\end{aligned} \tag{9}$$

Input voltages for converter II are:

$$\begin{aligned}
V_{b1} &= V_A - K_1 V_{AB} - K_2 V_{BC} \\
V_{b2} &= V_A - K_5 V_{AB} + K_6 V_{BC} \\
V_{b3} &= V_A - K_9 V_{AB} + K_{10} V_{BC} \\
V_{b4} &= V_B + K_{13} V_{AB} - K_{14} V_{CA} \\
V_{b5} &= V_B - K_{17} V_{BC} + K_{18} V_{CA} \\
V_{b6} &= V_B - K_{121} V_{BC} + K_{22} V_{CA} \\
V_{b7} &= V_C + K_{19} V_{BC} - K_{20} V_{AB} \\
V_{b8} &= V_C + K_{15} V_{BC} + K_{16} V_{AB} \\
V_{b9} &= V_C - K_{11} V_{CA} + K_{12} V_{AB} \\
V_{b10} &= V_A + K_7 V_{CA} - K_8 V_{BC} \\
V_{b11} &= V_A + K_3 V_{CA} - K_4 V_{BC}
\end{aligned} \tag{10}$$

Accordingly, the values of constants K_1-K_{22} are changed for retrofit applications as:

$$K_1 = 0.11607, K_2 = 0.092128, K_3 = 0.18219, K_4 = 0.13801,$$
$$K_5 = 0.22476, K_6 = 0.17409, K_7 = 0.40212, K_8 = 0.21852, \quad (11)$$
$$K_9 = 0.47375, K_{10} = 0.21103, K_{11} = 0.17013, K_{12} = 0.12381,$$
$$K_{13} = 0.14087, K_{14} = 0.07514, K_{15} = 0.11856, K_{16} = 0.00254,$$
$$K_{17} = 0.13346, K_{18} = 0.056973, K_{19} = 0.24100, K_{20} = 0.18386,$$
$$K_{21} = 0.29534, K_{22} = 0.20604.$$

The values of K1-K22 establish the essential turn numbers of the autotransformer windings to have the required output voltages and phase shifts. The kilovolt ampere rating of the autotransformer is calculated as [4]:

$$kVA = 0.5 \sum V_{winding} I_{winding} \quad (12)$$

Where, $V_{winding}$ is the voltage across each autotransformer winding and $I_{winding}$ indicates the full load current of the winding. Apparent power ratings of the tapped-interphase reactor and zero-sequence-blocking transformer (ZSBT) are also calculated in a same way.

C. Interphase Transformer

An overall schematic of the proposed 88-pulse ac-dc converter (shown in Fig. 4) is extracted from a 44-pulse ac-dc converter through adding a pulse doubling circuit in the DC link. The theory of pulse multiplication has been presented in [28] where a tapped inter-phase reactor along with two additional diodes are used to double the number of pulses in the supply line current resulting in current harmonic reduction. Afterwards, tapped interphase reactor was used in [26]-[31] to double the number of pulses in 12-pulse ac-dc converters. Furthermore, this type of multiplier was also served in paralleled thyristor bridge rectifiers [32]. Likewise, we used a tapped interphase rector (IPR) to extract an 88-pulse current from two paralleled 22-pulse rectifiers. The IPR and tapped diodes are shown in Fig. 5. For the pulse multiplication process, it is necessary to ensure that the average output voltages of bridges are equal and phase shifted of 8.18 degrees.

As two 22-pulse rectifiers are paralleled, the voltage across the interphase transformer, V_m, has a frequency 22 times that of the supply system. Therefore, size, weight and volume of the transformer reduce relative to rectifiers with a less pulse number.

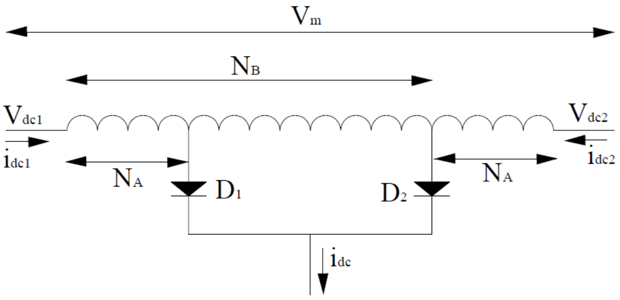

Fig. 5. Tapped Inter-phase Transformer circuit.

V_m is an alternating voltage with both positive and negative half cycles. Hence, D_1 conducts when the V_m is positive and, on the other hand, D_2 conducts when V_m is negative. The MMF equivalence between the windings when D_1 is on yields:

$$i_{dc1} N_A = i_{dc2} N_B \quad (13)$$

Where, N_A and N_B are number of turns as shown for IPR. We also have:

$$i_{dc1} + i_{dc2} = i_{dc} \quad (14)$$

Using (13) and (14), output current of the two rectifiers are calculated as follows:

$$i_{dc1} = (0.5 + K_t) i_{dc}$$
$$i_{dc2} = (0.5 - K_t) i_{dc} \quad (15)$$

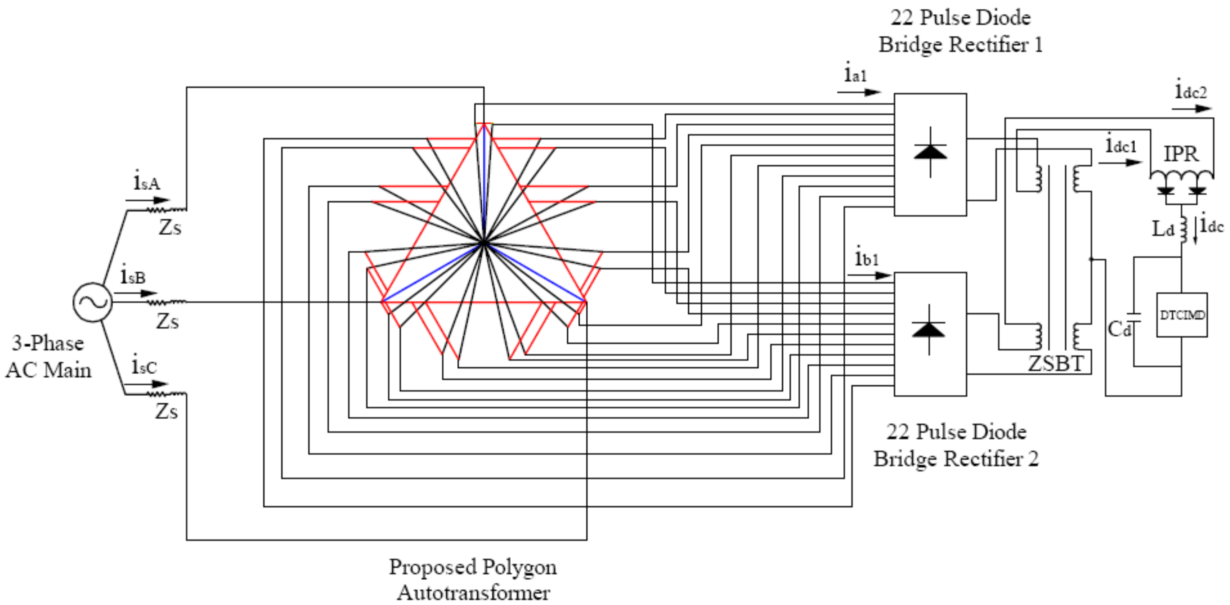

Fig.4. Polygon autotransformer configuration for 88-pulse ac–dc conversion.

In the above equation, $N_O=N_A+N_B$ and $K_t=(N_B-0.5N_O)/N_O$. The same relations can be written when V_m is in its negative half cycle. Therefore, according to MMF equation, the magnitude of output currents changes which results in pulse multiplication in the supply current. In [25], it is proved that K_t should be equal to 0.2457 to eliminate the harmonic currents up to the 37th order which can be applied in this application too.

D. Zero Sequence Blocking Transformer

In parallel-rectifier configurations, the two converters cannot be directly paralleled. Because, the output voltages are phase-shifted thereby unwanted conduction sequence of diodes is probable. Therefore, a zero-sequence-blocking transformer is required to ensure the independent operation of two paralleled rectifiers. In the proposed 88-pulse converter, the voltage frequency of ZSBT is 11 times that of the supply system and consequently it shows high impedance 11 ordered (and its multiples) current harmonics and prevents them to flow. Furthermore, high ripple frequency of the supply voltage in ZSBT makes it small and light.

III. MATLAB-BASED SIMULATION

Fig. 6 shows the implemented ac-dc converter with DTCIMD in MATLAB software using SIMULINK and power system block set (PSB) toolboxes. In this model, a three-phase 460 V and 60 Hz network is utilized as the supply for the 88-pulse converter. The designed autotransformer is modeled via three multi-winding transformers, as shown in Fig. 7. Multi-winding transformer block is also used to model ZSBT and IPT.

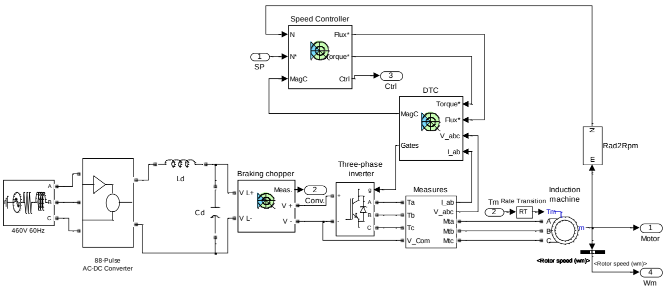

Fig. 6. Matlab model of 88-pulse ac–dc converter fed DTCIMD.

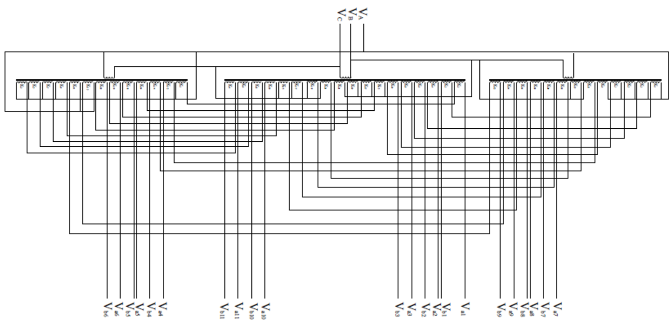

Fig. 7. Matlab model of proposed autotransformer for 88-pulse ac–dc converter system simulation.

At the converter output, a series inductance (L) and a parallel capacitor (C) as the dc link are connected to IGBT-based Voltage Source Inverter (VSI). VSI drives a squirrel cage induction motor employing direct torque-control strategy. The simulated motor is 50 hp (37.3 kW), 4-pole, and Y-connected. Detailed data of motor are listed in Appendix A. Simulation results are depicted in Figs. 8-22. Power quality parameters are also listed in Table I for 6-pulse, 44-pulse, and 88-pulse ac-dc converters.

IV. RESULTS AND DISCUSSION

Table I lists the power quality indices obtained from the simulation results of the 6-pulse, 44-pulse, and 88-pulse converters. Matlab block diagram of 88-pulse ac–dc converter system simulation, as shown in Fig. 8. Fig. 9 depicts two groups of 11-phase voltage waveforms with a phase shift of 8.18 degrees between the same voltages of each group. Diode D1 conducts when the voltage across the IPT (shown in Fig. 10) is positive and, conversely, D2 is on when the voltage across the IPT is in its negative half-cycle. The magneto motive force (MMF) equivalence of the IPT windings are formulated in equation (15) when D1 is on. This conduction sequence of the diodes is the basis of the pulse doubling technique. The current waveforms of these two diodes are shown in Fig. 11.

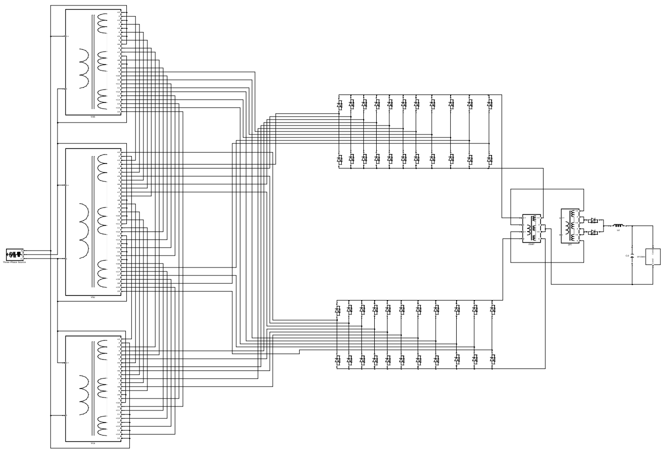

Fig. 8. Matlab block diagram of 88-pulse ac–dc converter system simulation.

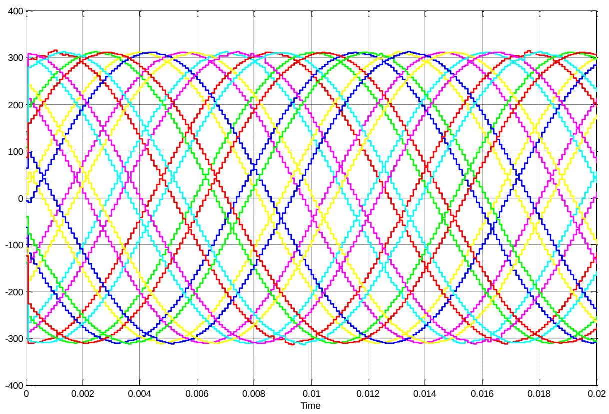

Fig. 9. 22-pulse autotransformer output voltage.

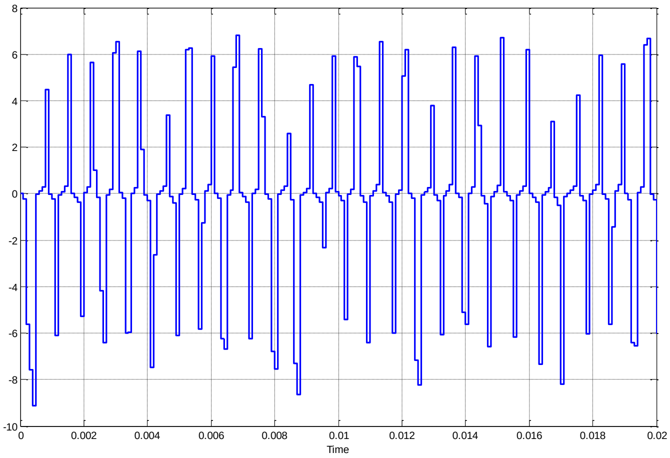

Fig. 10. Voltage waveform across the double-tap IPR

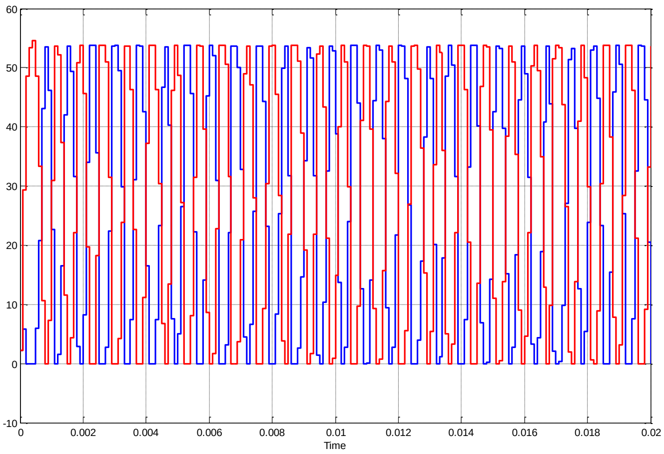

Fig. 11. Diodes D_1 and D_2 current waveforms.

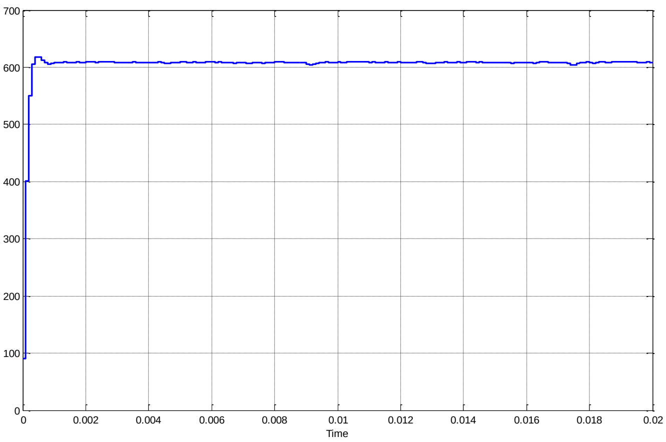

Fig. 12. 88-pulse ac–dc converter output voltage.

The voltage across the interphase transformer has a frequency equal to 22 times that of the supply which results in a significant reduction in volume and cost of magnetics. The 88-pulse converter output voltage (shown in Fig. 12) is almost smooth and free of ripples and its average value is 608.8 volts which is approximately equal to the DC link voltage of a six-pulse rectifier (607.9 volts). This makes the 88-pulse converter suitable for retrofit applications. Input current waveforms and its harmonic spectrum of the 6-pulse, 44-pulse, and 88-pulse converters extracted and shown in Figs. 13-18, respectively to check their consistency with the limitations of the IEEE standard 519.

These harmonic spectra are obtained when induction motor operates under light load (20% of full load) and full load conditions. Obviously, for 6-pulse converter, fifth and seventh order harmonics are dominant. Hence, input current THD of this converter will be relatively a large amount and is equal to 28.53% and 52.52% for full load and light load conditions that are not within the standard margins. On the other hand, as shown in Figs. 17-18, 88-pulse converter has an acceptable current THD (2.01% for light load and 1.60% for full load conditions). In this configuration, low order harmonics up to 85th are eliminated in the supply current.

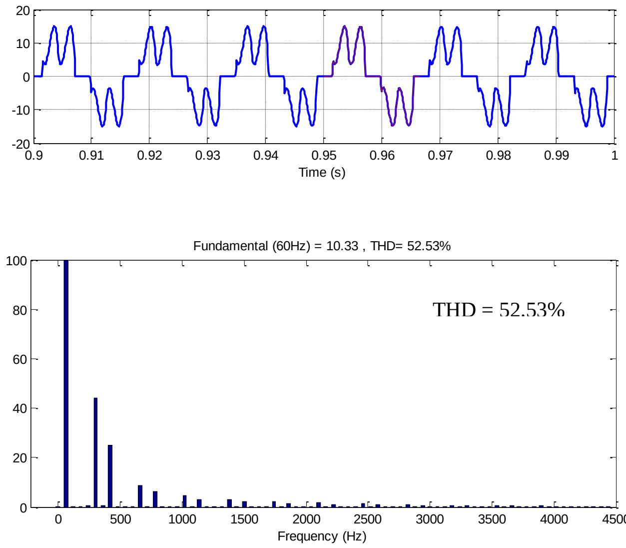

Fig. 13. Input current waveform of six-pulse ac–dc converter at light load and its harmonic spectrum.

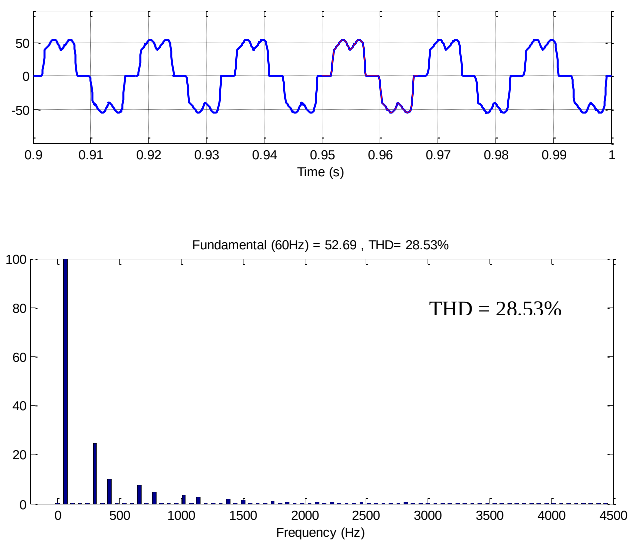

Fig. 14. Input current waveform of six-pulse ac–dc converter at full load and its harmonic spectrum

TABLE I
COMPARISON OF SIMULATED POWER QUALITY PARAMETERS OF THE VCIMD FED FROM DIFFERENT AC–DC CONVERTERS

Sr. No.	Topology	% THD of V_{ac}	AC Mains Current I_{SA} (A)		% THD of I_{SA}, at		Distortion Factor, DF		Displacement 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	5.64	10.33	52.69	52.53	28.53	0.8850	0.9599	0.9858	0.9881	0.8730	0.9485	616.6	607.6
2	44-pulse	1.68	10.62	53.34	2.94	1.89	0.998	0.999	0.997	0.997	0.996	0.997	613.1	609.1
3	88-pulse	1.50	10.78	52.32	2.01	1.60	0.9998	0.9998	0.9998	0.9993	0.9996	0.9990	611.3	608.8

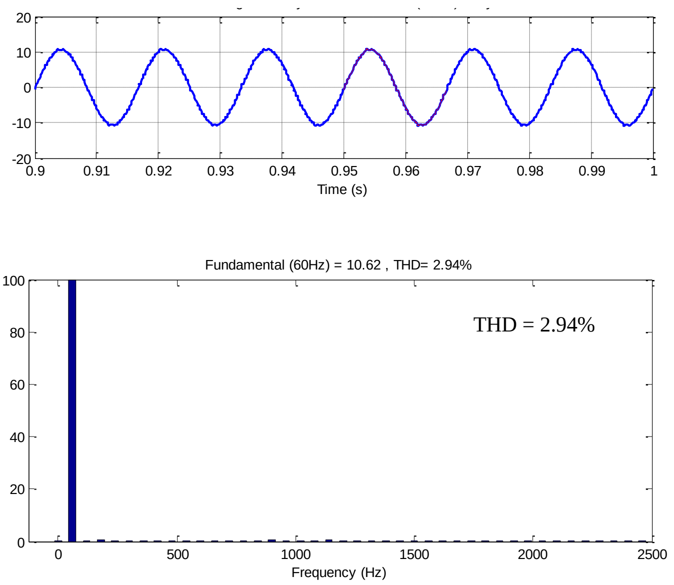

Fig. 15. Input current waveform of 44-pulse ac–dc converter at light load and its harmonic spectrum.

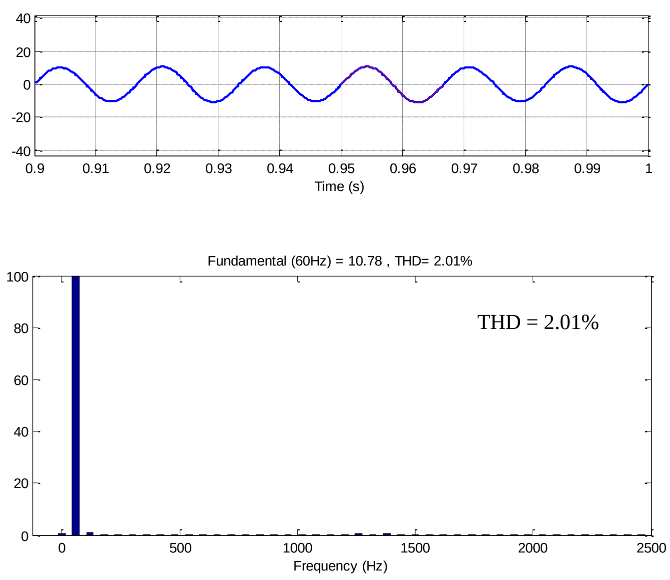

Fig. 17. Input current waveform of 88-pulse ac–dc converter at light load and its harmonic spectrum.

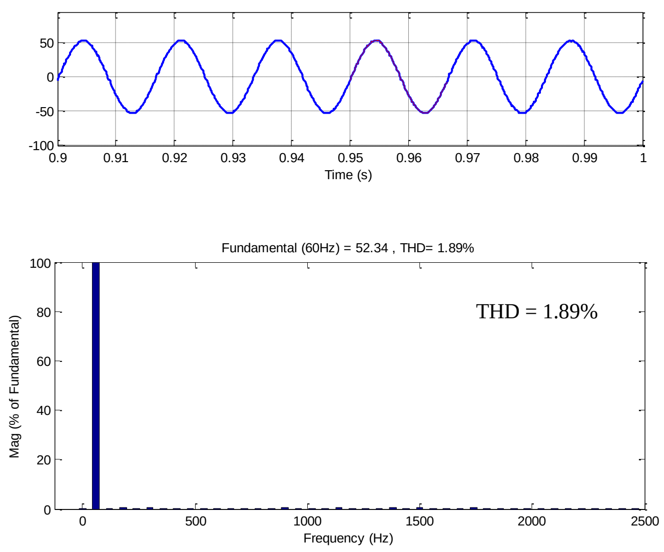

Fig. 16. Input current waveform of 44-pulse ac–dc converter at full load and its harmonic spectrum.

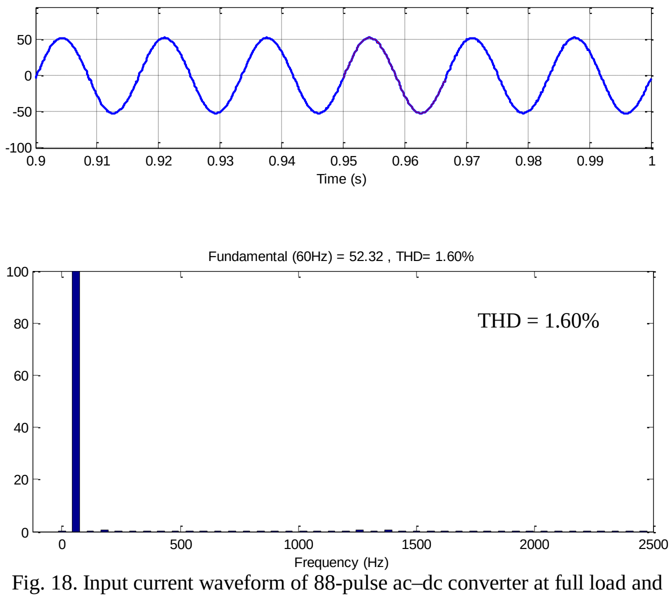

Fig. 18. Input current waveform of 88-pulse ac–dc converter at full load and its harmonic spectrum.

TABLE II
COMPARISON OF POWER QUALITY INDICES OF PROPOSED 88-PULSE AC-DC CONVERTER

Load (%)	THD (%)		CF of I_S	DF	DPF	PF	RF (%)	V_{dc} (V)
	I_S	V_S						
20	2.01	0.70	1.4	0.9998	0.9998	0.9996	0.002	611.3
40	1.63	0.93	1.4	0.9998	0.9997	0.9995	0.004	610.8
60	1.94	1.14	1.4	0.9998	0.9996	0.9994	0.003	610.2
80	1.58	1.25	1.4	0.9998	0.9994	0.9992	0.006	609.5
100	1.60	1.50	1.4	0.9998	0.9993	0.9990	0.002	608.8

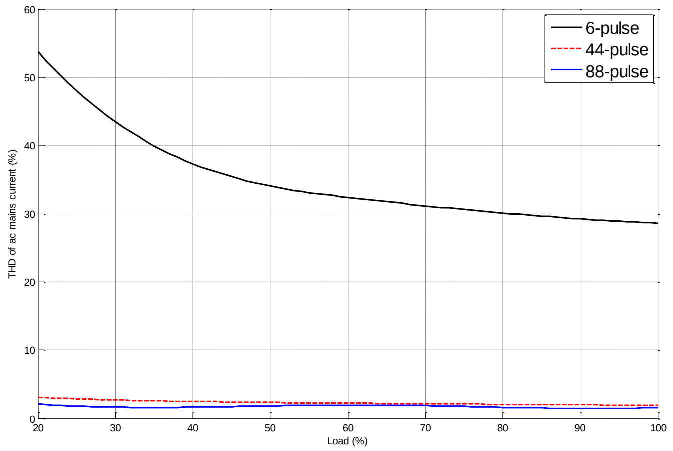

Fig. 19. Variation of THD with load on DTCIMD in 6-pulse, 44-pulse and 88-pulse ac-dc converter.

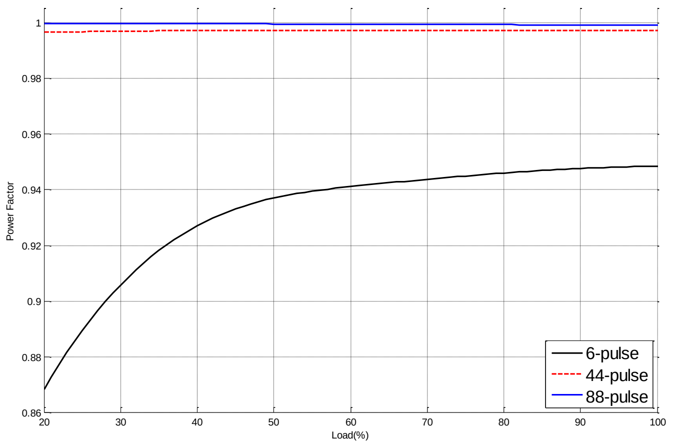

Fig. 20. Variation of power factor with load on DTCIMD in 6-pulse, 44-pulse and 88-pulse ac-dc converter.

In general, the largely improved performance of the 88-pulse converter makes the power quality indices such as THD of supply current and voltage (THDi and THDv), displacement power factor (DPF), distortion factor (DF), and power factor (PF) satisfactory for different loading conditions. The aforementioned criteria are listed in Table I for the three types of converters.

Different power quality indices of the proposed topology under different loading conditions are shown in Table II. Results show that even under load variations, the 88-pulse converter has an improved performance and the current THD is always less than 2% for all loading conditions. Input current THD and power factor variations are also shown in Figs. 19 and 20 respectively, for 6-pulse, 44-pulse, and 88-pulse ac-dc converters. Results show that the input current corresponding to the proposed configuration has an almost unity power factor. Furthermore, in the worst case (light loads) the current THD has reached below 2% for the proposed topology.

V. CONCLUSION

A novel polygon-connected autotransformer was designed and modeled to make an 88-pulse ac-dc converter with DTCIMD load. Afterwards, the proposed design procedure was modified for retrofit applications. A zero-sequence-blocking transformer was added to ensure the independent operation of paralleled rectifiers and a tapped inter-phase reactor was used to double the number of pulses in the ac mains currents. The increased number of pulses results in the frequency increase of the supply voltages of ZSBT and IPR, thereby decreasing the size and volume of the transformers. In addition, a laboratory prototype was constructed to show the applicability of the proposed converter. Simulation and experimental results prove that, for the proposed topology, input current distortion factor is in a good agreement with IEEE 519 requirements. Current THD is less than 2% for varying loads. It was also observed that the input power factor is close to unity resulting in reduced input current for DTCIMD load. In brief, power quality improvement of the supply current and reduced ratings of the transformers and consequently reduced cost of converter are the major benefits of the proposed 88-pulse ac-dc converter.

APPENDIX

A. *Motor and Controller Specifications*

Three-phase squirrel cage induction motor—50 hp (37.3 kW), three phase, four pole, Y-connected, 460 V, 60 Hz. R_s = 0.0148 Ω; R_r = 0.0092 Ω; X_{ls} = 1.14Ω; X_{lr} = 1.14 Ω, X_{Lm} = 3.94 Ω, J = 3.1 Kg · m^2.

Controller parameters: PI controller Kp = 300; Ki = 2000.

DC link parameters: L_d = 2 mH; C_d = 3200 μF.

Source impedance: Z_s = j0.1884 Ω (=3%).

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Rohollah. Abdollahi was born in Qom, Iran, in 1983. He received the B.Sc. degree in electrical engineering from Buali Sina University, Hamedan, Iran, in 2007 and the M.Sc. degree in electrical engineering (power electronics and electrical machines) from Iran University of Science and Technology, Tehran, Iran, in 2011. He joined the Qom Branch, Islamic Azad University, Qom, Iran. He is the author of more than 20 journal and 5 conference papers and 8 Patents. His principle research interests are: Power electronics, Power quality, and Electrical machines. Mr. Abdollahi is a member of Iran's National Elite Foundation and a member of Iranian organization for engineering order of building and a member of the Iranian association of electrical & Electronics Engineers.