Design and construction of a polygon-connected autotransformer-based 36-pulse AC-DC converter for power quality improvement in retrofit applications

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Abstract. This paper presents the design and analysis of a polygon connected autotransformer based 36-phase AC-DC converter which supplies direct torque controlled induction motor drives (DTCIMD's) in order to have better power quality conditions at the point of common coupling. The proposed converter output voltage is accomplished via two paralleled eighteen-pulse AC-DC converters each of them consisting of nine-phase diode bridge rectifier. An autotransformer is designed to supply the rectifier. 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. The proposed 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 and proposed converters from view point of power quality indices. Results show that input current total harmonic distortion (THD) is less than 4% for the proposed topology at variable loads. A laboratory prototype of the proposed Polygon-Connected autotransformer-based 36-pulse AC-DC converter is developed and test results are presented to validate the developed design procedure and the simulation models of this AC-DC converter under varying loads.

Key words: AC-DC converter, polygon autotransformer, power quality, 36-pulse rectifier, direct torque controlled induction motor drive (DTCIMD).

1. 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 the torque controlled technique is implemented in a voltage source inverter which is mostly fed from the 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 DTCIMD's should be confined within the standard limitations. The most prominent standards in this field are IEEE standard 519 [2] and the International Electrotechnical 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 multipulse AC-DC converters. These converters are based on either phase multiplication or phase shifting or pulse doubling or a combination [4–29].

Although, in the conditions of light load or small source impedance, line current total harmonic distortion (THD) is more than 5% for up to 18-pulse AC-DC converters. A Zigzag-Connected Autotransformer-Based 24-pulse AC-DC converter is reported in [10] which has THD variation of 4.51% to 5.77% from full-load to light-load (20% of full-load). Another T-Connected Autotransformer-Based 24-Pulse AC-DC Converter has also been presented in [15], however, the THD of the supply current with this topology is reported to vary from 2.46% to 520% which is more than 5% when operating at light load The 36-pulse one was designed for vector controlled induction motor drives in [27] which has THD variation of 2.03% to 3.74% from full-load to light-load (20% of full-load) respectively but the dc link voltage is higher than that of a 6-pulse diode bridge rectifier, thus making the scheme nonapplicable for retrofit applications.

The Delta/Polygon-connected transformer-based 36-pulse AC-DC converter for power quality improvement in [28] which has THD variation of 2.93% to 3.95% from full-load to light-load (20% of full-load) respectively and Delta/Fork-connected transformer-based 36-pulse AC-DC converters have

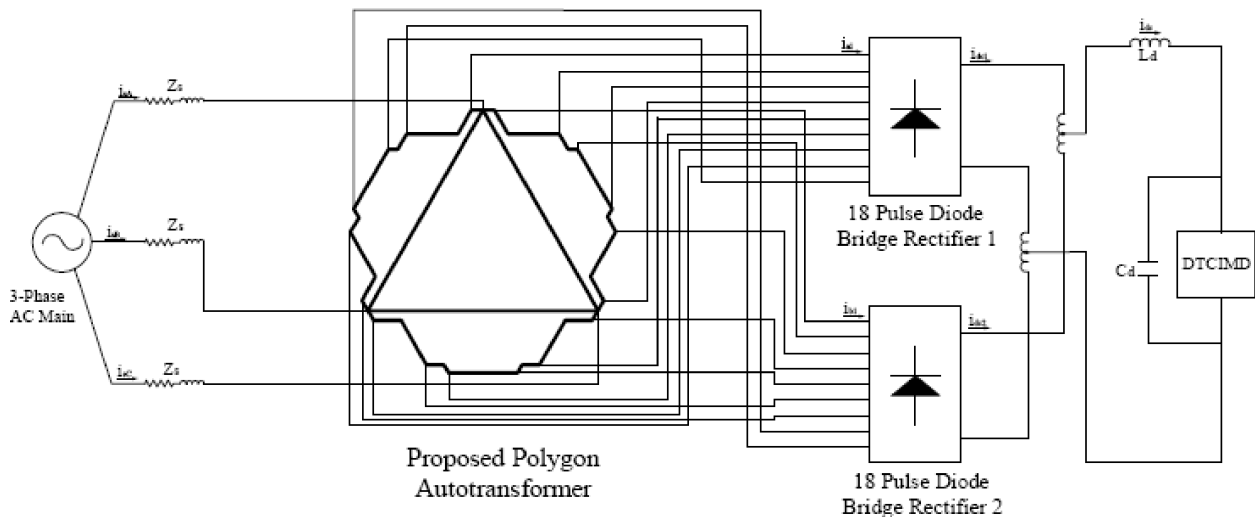*e-mail: Rohollah.abdollahi@yahoo.com

Fig. 1. Polygon-autotransformer configuration for 36-pulse AC-DC conversion

been reported [29] for reducing the total harmonic distortion (THD) of the ac mains current. But these topologies require higher rating magnetics, resulting in the enhancement of capital cost. However, this topologies increase the rating of magnetic parts, which finally affects the total cost of the project. In contrast, the autotransformer-based configurations [4] reduce the ratings of magnetic parts. This is true because of the fact that in this topology, only a portion of KVA rating of the induction motor should be beard by the magnetic coupling parts. Therefore, autotransformer-based configurations could significantly reduce the size and proportionally the weight of the transformer.

As is mentioned before, in this paper, a 36-pulse AC-DC converter is proposed employing a novel polygon autotransformer The Polygon-connected platform could simplify the resulted configuration for the converters and reducing the costs. In fact, this is a tradeoff between the pulse number, transformer platform, complexity of the scheme and the cost off the configuration. The proposed scheme has an optimized configuration in this regard. 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. The proposed design method will be suitable even when the transformer output voltages vary while keeping its 36-pulse operation. In the proposed structure, two nine-leg diode-bridge rectifiers are paralleled via two interphase transformers (IPTs) and fed from an autotransformer. Hence, a 36-pulse output voltage is obtained. Detailed design tips of the IPT and totally the whole structure of 36-pulse AC-DC converter are described in this paper and the proposed converter is modeled and simulated in MATLAB to study its behavior and specifically to analyze the power quality indices at ac mains.

Furthermore, a 36-pulse AC-DC converter consisting of a polygon autotransformer, two eighteen-pulse diode bridge rectifiers paralleled through two IPTs, and with a DTCIMD load Fig. 1. Simulation results of six-pulse and proposed 36-pulse AC-DC converters feeding a DTCIMD load are sched-

uled 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. Finally, a small-rating laboratory prototype of the proposed autotransformer-based 36-pulse is constructed and different tests are managed to verify the proposed harmonic mitigating structure. It is shown that simulation results are in a good agreement with experimental results under different operating conditions.

2. Proposed 20-pulse AC-DC converter

In order to implement a 36-pulse AC-DC converter through paralleling two bridge rectifiers, i.e. two 18-pulse rectifiers, two sets of nine-phase voltages with a phase difference of 40 degrees between the voltages of each group and 10 degrees between the same voltages of the two groups are required.

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

2.1. Design of proposed autotransformer for 36-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}) and (V_{b1}, V_{b2}, V_{b3}, V_{b4}, V_{b5} V_{b6}, V_{b7}, V_{b8}, V_{b9}) 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 10 degrees. V_{a1} and V_{b1} has a phase shift of $+5$ and -5 degrees from the input voltage of phase A, respectively. According to a phasor diagram, the nine-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:

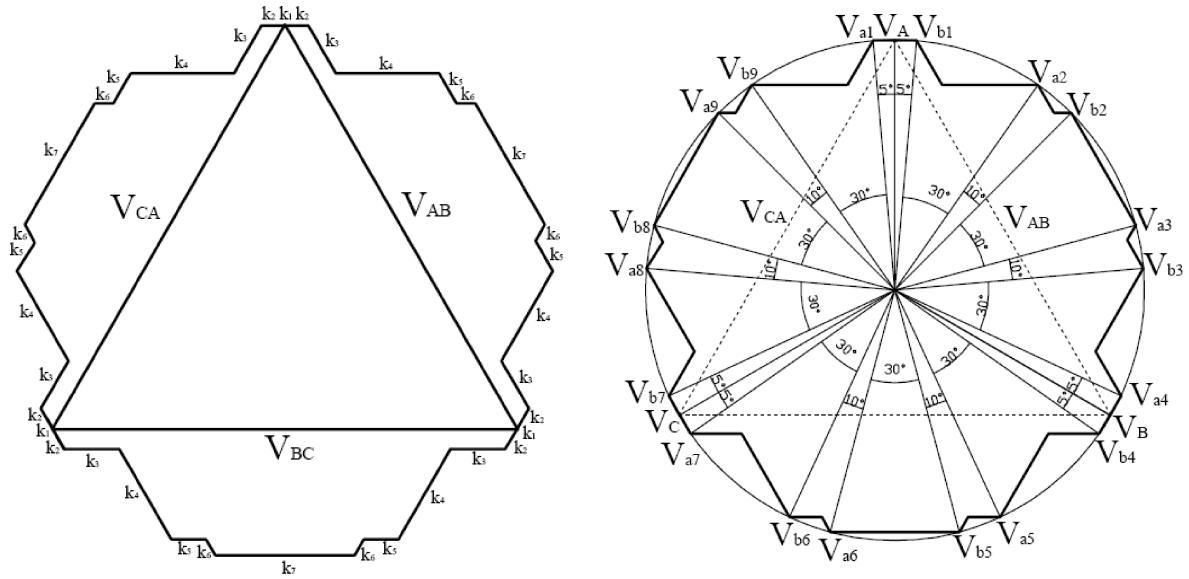$$V_A = V_s\angle 0°, \quad V_B = V_s\angle -120°, \quad V_C = V_s\angle 120°. \quad (1)$$

Fig. 2. Polygon connection of proposed autotransformer for 36-pulse converter and its phasor representation

Where, nine-phase voltages are:

$$V_{a1} = V_s\angle+5°, \quad V_{a2} = V_s\angle-35°,$$

$$V_{a3} = V_s\angle-75°, \quad V_{a4} = V_s\angle-115°,$$

$$V_{a5} = V_s\angle-155°, \quad V_{a6} = V_s\angle-195°, \quad (2)$$

$$V_{a7} = V_s\angle-235°, \quad V_{a8} = V_s\angle-275°,$$

$$V_{a9} = V_s\angle-315°.$$

$$V_{b1} = V_s\angle-5°, \quad V_{b2} = V_s\angle-45°,$$

$$V_{b3} = V_s\angle-85°, \quad V_{b4} = V_s\angle-125°,$$

$$V_{b5} = V_s\angle-165°, \quad V_{b6} = V_s\angle-205°, \quad (3)$$

$$V_{b7} = V_s\angle-245°, \quad V_{b8} = V_s\angle-285°,$$

$$V_{b9} = V_s\angle-325°.$$

Input voltages for converter I are:

$$V_{a1} = V_A + K_1 V_{CA} - K_2 V_{BC},$$

$$V_{a2} = V_{b1} - K_3 V_{AB} + K_4 V_{BC},$$

$$V_{a3} = V_{b2} - K_7 V_{AB},$$

$$V_{a4} = V_B + K_1 V_{AB} - K_2 V_{CA},$$

$$V_{a5} = V_{b4} - K_3 V_{BC} + K_4 V_{CA}, \quad (4)$$

$$V_{a6} = V_{b5} - K_7 V_{BC},$$

$$V_{a7} = V_C + K_1 V_{BC} - K_2 V_{AB},$$

$$V_{a8} = V_{b7} - K_3 V_{CA} + K_4 V_{AB},$$

$$V_{a9} = V_{b8} - K_7 V_{CA}.$$

Input voltages for converter II are:

$$V_{b1} = V_A - K_1 V_{AB} + K_2 V_{BC},$$

$$V_{b2} = V_{a2} - K_5 V_{AB} + K_6 V_{BC},$$

$$V_{b3} = V_{a3} + K_6 V_{CA} - K_5 V_{AB},$$

$$V_{b4} = V_B - K_1 V_{BC} + K_2 V_{CA},$$

$$V_{b5} = V_{a5} - K_5 V_{BC} + K_6 V_{CA}, \quad (5)$$

$$V_{b6} = V_{a6} + K_6 V_{AB} - K_5 V_{BC},$$

$$V_{b7} = V_C - K_1 V_{CA} + K_2 V_{AB},$$

$$V_{b8} = V_{a8} - K_5 V_{CA} + K_6 V_{AB},$$

$$V_{b9} = V_{a9} + K_6 V_{BC} - K_5 V_{CA},$$

$$V_{AB} = \sqrt{3}V_A\angle30°, \qquad V_{BC} = \sqrt{3}V_B\angle30°,$$

$$V_{CA} = \sqrt{3}V_C\angle30°. \quad (6)$$

Constants K_1-K_7 are calculated using (2)–(6) to obtain the required windings turn numbers to have the desired phase shift for the two voltage sets:

$$K_1 = 0.00254, \quad K_2 = 0.04904, \quad K_3 = 0.11802,$$
$$K_4 = 0.22183, \quad K_5 = 0.0747, \quad K_6 = 0.039747, \quad (7)$$
$$K_7 = 0.29886.$$

2.2. 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 36-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.
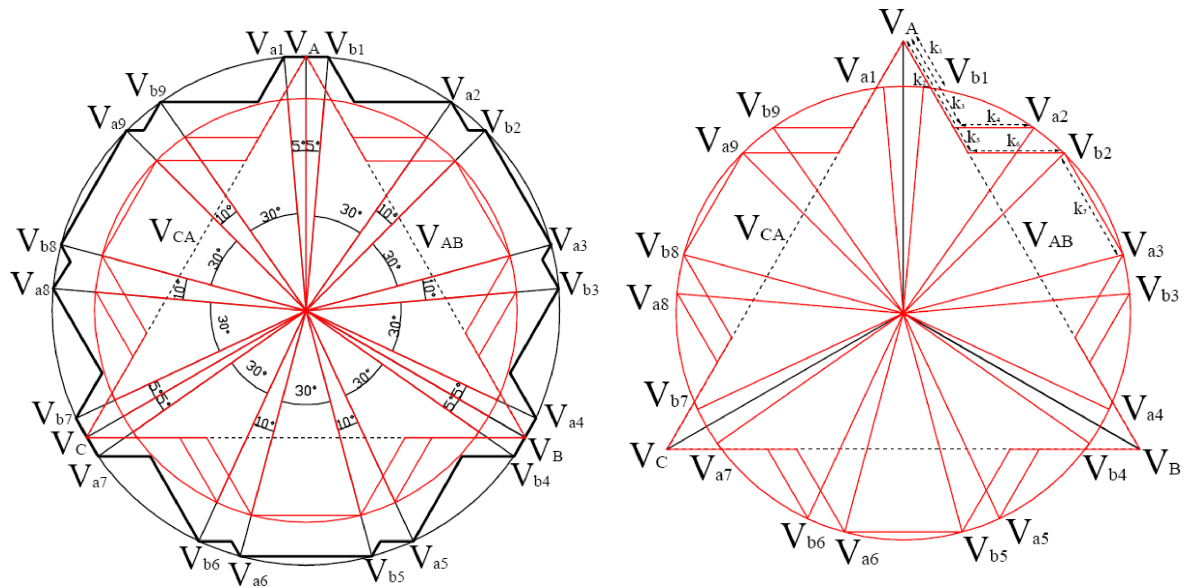
Fig. 3. Phasor diagram of voltages in the proposed autotransformer connection along with modifications for retrofit arrangement

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 Sec. 2 part 1, the following equations can be derived as:

$$|V_S| = 0.8328\,|V_A|. \tag{8}$$

Input voltages for converter I are:

$$
\begin{aligned}
V_{a1} &= V_A + K_1 V_{CA} + K_2 V_{BC}, \\
V_{a2} &= V_A - K_3 V_{AB} + K_4 V_{BC}, \\
V_{a3} &= V_B + K_5 V_{AB} - K_6 V_{CA}, \\
V_{a4} &= V_B + K_1 V_{AB} + K_2 V_{CA}, \\
V_{a5} &= V_B - K_3 V_{BC} + K_4 V_{CA}, \\
V_{a6} &= V_C + K_5 V_{BC} - K_6 V_{AB}, \\
V_{a7} &= V_C + K_1 V_{BC} + K_2 V_{AB}, \\
V_{a8} &= V_C - K_3 V_{CA} + K_4 V_{AB}, \\
V_{a9} &= V_A + K_5 V_{CA} - K_6 V_{BC}.
\end{aligned}
\tag{9}
$$

Input voltages for converter II are:

$$
\begin{aligned}
V_{b1} &= V_A - K_1 V_{AB} - K_2 V_{BC}, \\
V_{b2} &= V_A - K_5 V_{AB} + K_6 V_{BC}, \\
V_{b3} &= V_B + K_3 V_{AB} - K_4 V_{CA}, \\
V_{b4} &= V_B - K_1 V_{BC} - K_2 V_{CA}, \\
V_{b5} &= V_B - K_5 V_{BC} + K_6 V_{CA}, \\
V_{b6} &= V_C + K_3 V_{BC} - K_6 4 V_{AB}, \\
V_{b7} &= V_C - K_1 V_{CA} - K_2 V_{AB}, \\
V_{b8} &= V_C - K_5 V_{CA} + K_6 V_{AB}, \\
V_{b9} &= V_A + K_3 V_{CA} - K_4 V_{BC}.
\end{aligned}
\tag{10}
$$

Accordingly, the values of constants K_1-K_7 are changed for retrofit applications as:

$$K_1 = 0.1136, \quad K_2 = 0.01489, \quad K_3 = 0.21188,$$

$$K_4 = 0.16985, \quad K_5 = 0.27408, \quad K_6 = 0.20295, \tag{11}$$

$$K_7 = 0.24888.$$

The values of K_1-K_7 establish the essential turn numbers of the autotransformer windings to have the required output voltages and phase shifts.

To ensure the independent operation of the rectifier groups, interphase transformers (IPTs), which are relatively small in size, are connected at the output of the rectifier bridges. With this arrangement, the rectifier diodes conduct for 120 per cycle. The kilovoltampere rating of the autotransformer is calculated as [4]:

$$kVA = 0.5 \sum V_{\text{winding}} I_{\text{winding}}, \tag{12}$$

where V_{winding} is the voltage across each autotransformer winding and I_{winding} indicates the full load current of the winding. The apparent power rating of the interphase transformer is also calculated in a same way.

3. Matlab-based simulation

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 36-pulse converter. The designed autotransformer is modeled via three multi-winding transformers. Multi-winding transformer block is also used to model IPT Detailed data of 36-pulse converter are listed in Appendix A.

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. 4–9. Power quality parameters are also listed in Table 1 for 6-pulse and 36-pulse AC-DC converters. The rating of input transformer is calculated based on the simulated rms values of the voltage and current.
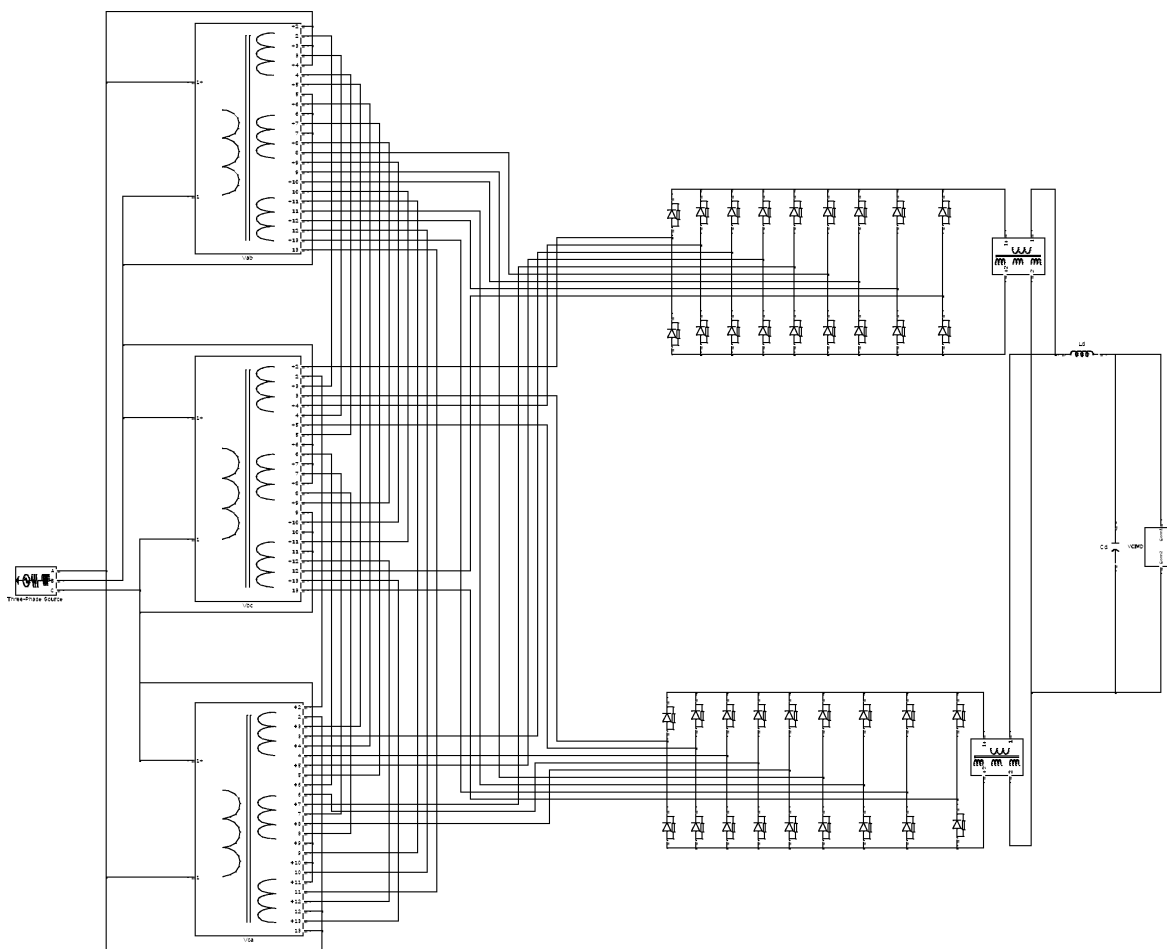

Fig. 4. Matlab block diagram of 36-pulse AC-DC converter system simulation
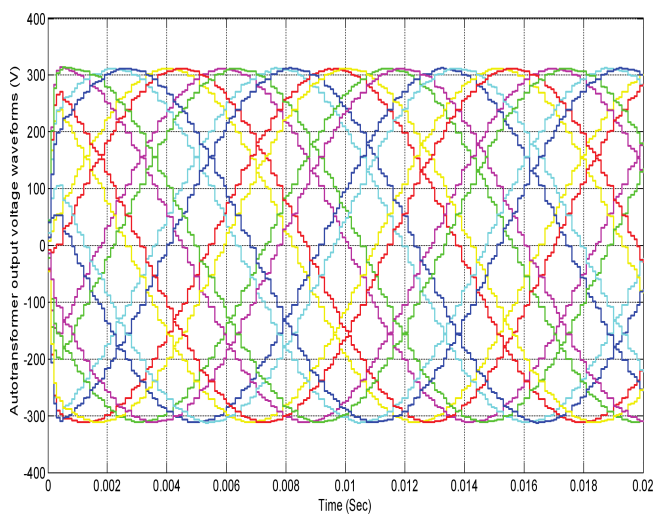

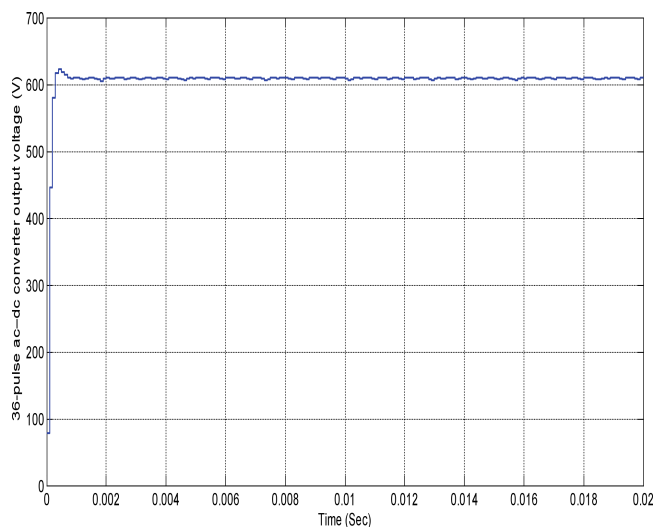Fig. 5. Autotransformer output voltage

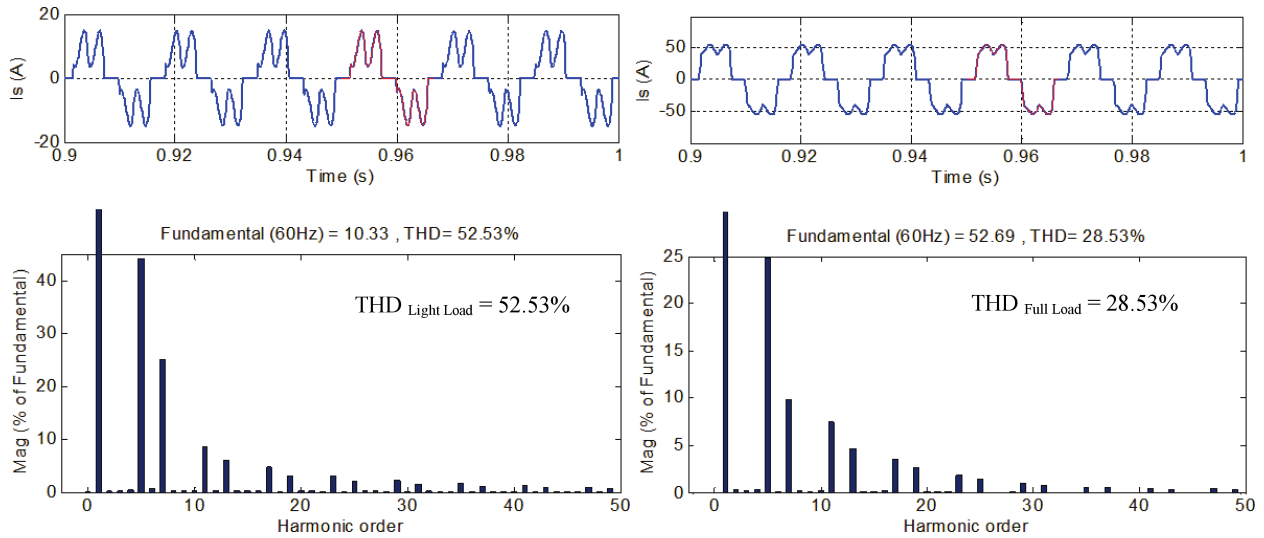Fig. 6. 36-pulse AC-DC converter output voltage

Fig. 7. Input current waveform of six-pulse AC-DC converter at light load and its harmonic spectrum at light load and full load (50hp load)
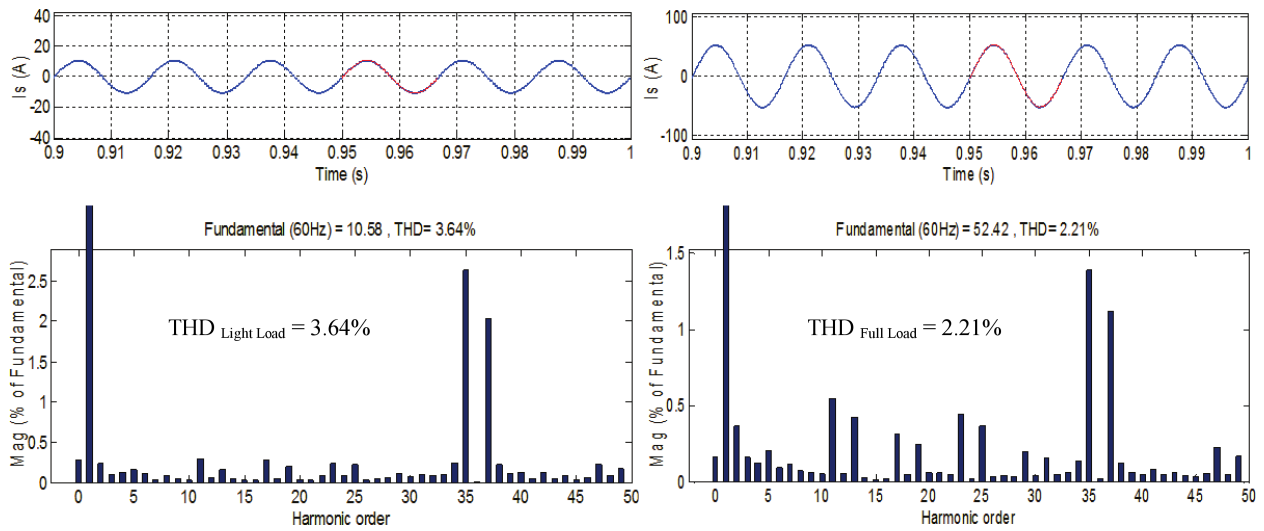

Fig. 8. Input current waveform of 36-pulse AC-DC converter and its harmonic spectrum at light load and full load (50hp load)
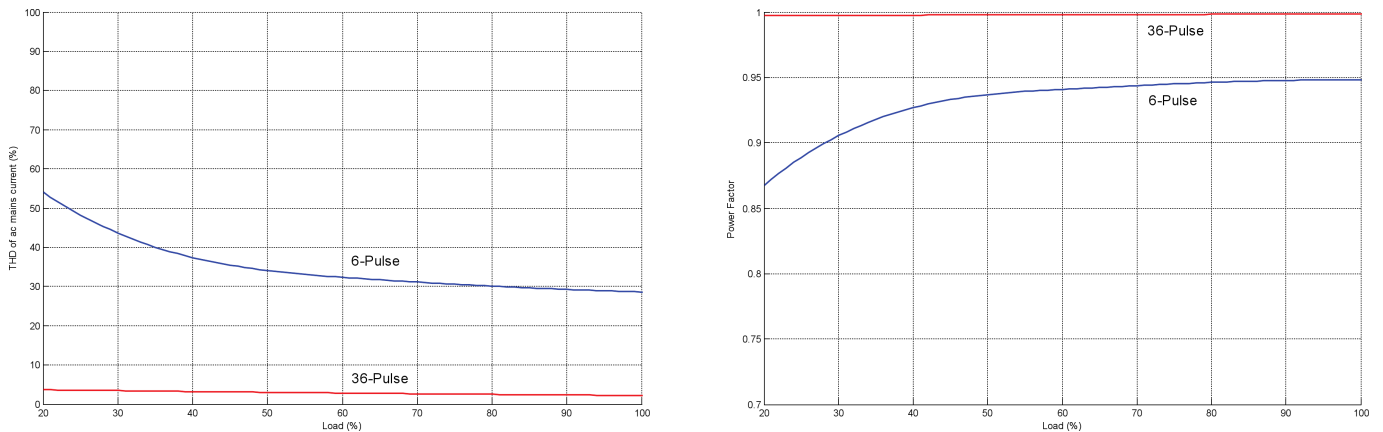

Fig. 9. Variation of THD and power factor with load on DTCIMD in 6-pulse and 36-pulse AC-DC converter

Table 1
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	36-pulse	2.16	10.57	52.45	3.64	2.21	0.9993	0.9995	0.9992	0.9981	0.9985	0.9976	612.7	608.9

4. Experimentation

In order to verify the theoretical approach and show the applicability of the proposed topology, a laboratory prototype of the polygon-connected autotransformer-based 36-pulse AC-DC converter is constructed that is shown in Fig. 10 An autotransformer for 36-pulse AC-DC converter has been designed and developed in the laboratory. The winding details of the developed autotransformers are given in Appendix B.

Various tests have been conducted under Three-phase voltages with phase to phase rms value of 380 volts and an equivalent resistive load. Input voltage and current waveforms and harmonic spectra of the ac mains currents are extracted from simulations and experiments for 6-pulse and 36-pulse converters and shown in Figs. 11, 12 respectively. In the experiments, a HWT −1000 power analyzer is used as the measuring apparatus.
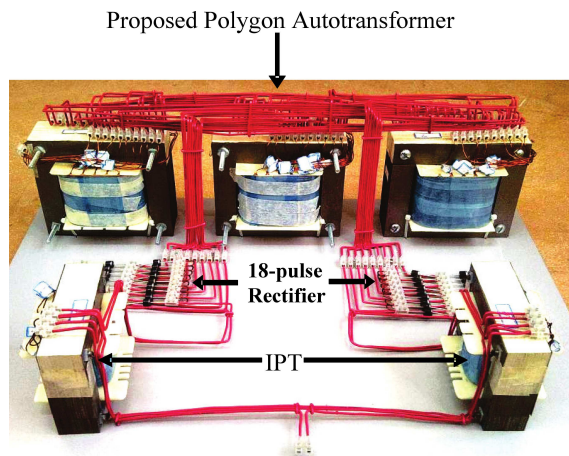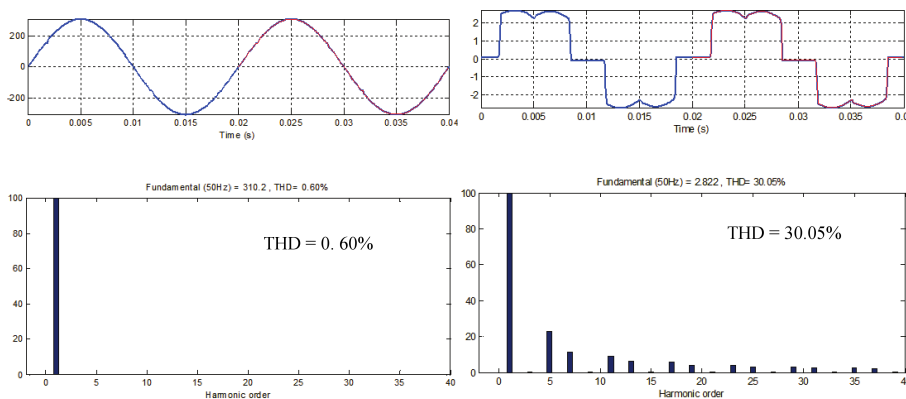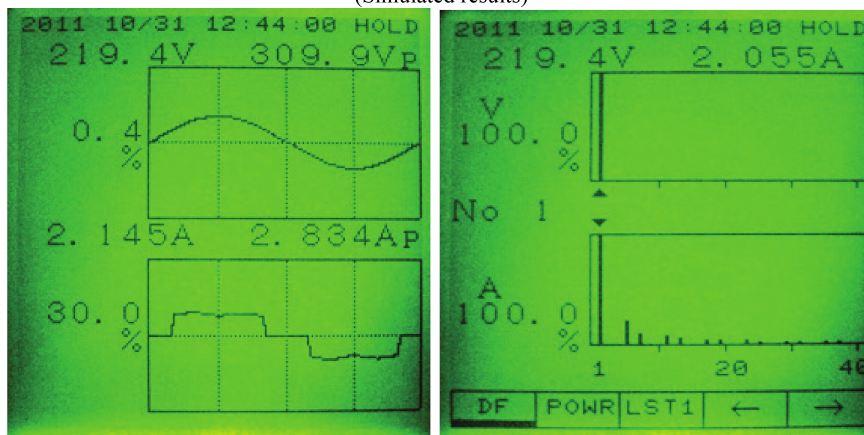

Fig. 10. Laboratory prototype of the proposed Polygon-Connected autotransformer-based 36-pulse AC-DC converter

(Simulated results)

(Experimental results)

Fig. 11. Input voltage and current waveform with their harmonic spectrum in simulation as well as experimentation for 6-pulse AC-DC conversion with light load (10hp load)
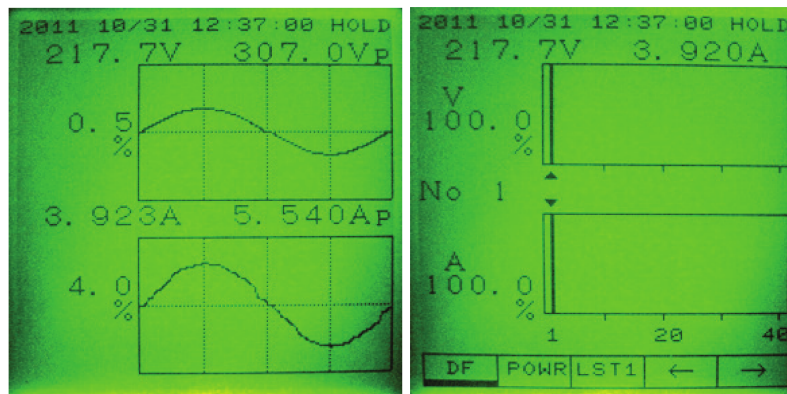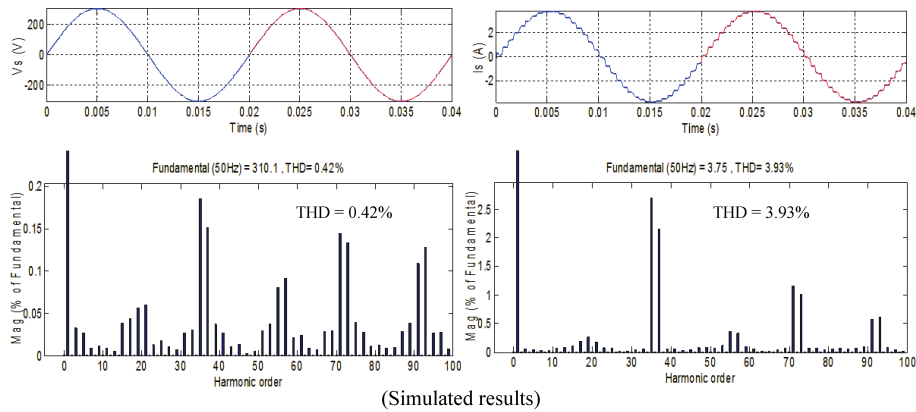
(Simulated results)

(Experimental results)

Fig. 12. Input voltage and current waveform with their harmonic spectrum in simulation as well as experimentation for 36-pulse AC-DC conversion with light load (10hp load)

5. Results and discussion

Table 1 lists the power quality indices obtained from the simulation results of the 6-pulse and 36-pulse converters. The Matlab block diagram of 36-pulse AC-DC converter system simulation, as shown in Figs. 4 and 5 depicts two groups of nine-phase voltage waveforms with a phase shift of 1 degrees between the same voltages of each group.

The voltage across the interphase transformer has a frequency equal to 9 times that of the supply which results in a significant reduction in volume and cost of magnetics. The 36-pulse converter output voltage (shown in Fig. 6) is almost smooth and free of ripples and its average value is 608.9 volts which is approximately equal to the DC link voltage of a six-pulse rectifier (607.6 volts). This makes the 36-pulse converter suitable for retrofit applications.

Input current waveforms and its harmonic spectrum of the 6-pulseand 36-pulse converters extracted and shown in Figs. 7, and 8, respectively to check their consistency with the limitations of the IEEE standard 519. These harmonic spectrums 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 52.53% for full load and light load conditions that are not within the

standard margins. On the other hand, as shown in Fig. 8, 36-pulse converter has an acceptable current THD (3.64% for light load and 2.21% for full load conditions). In this configuration, low order harmonics up to 33rd are eliminated in the supply current.

In general, the largely improved performance of the 36-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 1 for the three types of converters. Input current THD and power factor variations are also shown in Fig. 9, for 6-pulse, and 36-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 4% for the proposed topology

Different power quality indices of the proposed topology under different loading conditions are shown in Table 2. Results show that even under load variations, the 36-pulse converter has an improved performance and the current THD is always less than 4% for all loading conditions.

In order to verify the theoretical approach and demonstrate the applicability of the proposed topology, a laboratory prototype of conventional 6-pulse and the proposed 36-pulse

converters (Fig. 1) are constructed. Several tests have been carried out using an equivalent resistive load under light load to demonstrate the worst case harmonic conditions. Input line current waveforms and their harmonic spectrum for 6-pulse, 36-pulse converters are extracted using a HWT-1000 harmonic analyzer and shown in Figs. 11, 12 respectively.

Table 2
Comparison of power quality indices of proposed 36-pulse AC-DC converter

Load [%]	THD [%]		CF of I_S	DF	DPF	TPF	RF [%]	V_{dc} [V]
	I_S	V_S						
20	3.64	0.93	1.413	0.9993	0.9992	0.9985	0.002	612.7
40	3.20	1.35	1.414	0.9994	0.9989	0.9983	0.003	611.8
60	2.81	1.68	1.414	0.9995	0.9985	0.9980	0.005	610.9
80	2.47	2.01	1.414	0.9995	0.9982	0.9977	0.003	609.9
100	2.21	2.16	1.414	0.9995	0.9980	0.9976	0.006	608.9

Some experiments are carried out to validate the design approach of the converter ant the results are shown in Figs. 11, 12. The ratings of input transformer and IPT are estimated, and these are 43.77%, and 0.38%, respectively of the load rating. As mentioned previously, the required magnetic ratings of the proposed topology is 44.15% of the load rating while THDi<4% is achieved Agreement between the simulation and experimental results indicates the suitability and capability of the proposed topology for various industry applications without violating power quality standard limits.

6. Conclusions

A novel polygon-connected autotransformer was designed and modeled to make a 36-pulse AC-DC converter with DTCIMD load. The proposed converter output voltage is accomplished via two paralleled eighteen-pulse AC-DC converters each of them consisting of nine-phase diode bridge rectifier. Afterwards, the proposed design procedure was modified for retrofit applications. 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 4% 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 36-pulse AC-DC converter.

Appendix A.
Motor and controller and 36-pulse converter specifications

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

Controller parameters: PI controller Kp = 300; Ki = 2000 DC link parameters: $L_d = 2$ mH; $C_d = 3200\ \mu$F. Source impedance: $Z_s = j0.1884\ \Omega$ (=3%).

36-pulse converter: The designed autotransformer is modeled via three multi-winding transformers (refer to Fig. 4) T_{AB}, T_{BC}, and T_{CA} as following details: The various winding nominal voltages (Vrms) of transformers T_{AB} [1 0.1136 0.21188 0.27408 0.27408 0.21188 0.1136 0.20295 0.16985 0.01489 0.01489 0.16985 0.20295]*460. The various winding nominal voltages (Vrms) of transformers T_{BC} [1 0.01489 0.01489 0.16985 0.20295 0.1136 0.21188 0.27408 0.27408 0.21188 0.1136 0.20295 0.16985]*460, and the various winding nominal voltages (Vrms) of transformers T_{CA} [1 0.1136 0.20295 0.16985 0.01489 0.01489 0.16985 0.20295 0.1136 0.21188 0.27408 0.27408 0.21188]*460.
IPT: The various winding nominal voltages (Vrms) of transformers T_{IPT} [20 20].
Multi-winding transformer block is also used to model IPT.
Autotransformer leakage inductance: $L_T = 0.0001$ pu ($X_{LT} = 0.04$ pu).
DC link parameters: $L_d = 0.02$ mH (0.001 pu); $C_d = 3200\ \mu$F (0.15 pu).
Source impedance: $Z_s = j0.1884\ \Omega$ (=0.03 pu).

7. Appendix B.
Details of developed autotransformer, IPT

The autotransformer is made up of three single-phase transformers (refer to Fig. 23) T$_{AB}$, T$_{BC}$, and T$_{CA}$ as following details: Flux density = 0.8 T; Current density = 2.3 A/mm2; Core size: E-Laminations: Length = 17 cm, Width = 11.5 cm; I-Laminations: Length = 17 cm, Width = 2.85 cm. The number of turns for various windings of transformers T$_{AB}$ (1091.5 VA) are 61.5, 114.5, 148, 148, 114.5, 61.5, 109.5, 91.5, 8, 8, 91.5, 109.5, 539.5 and wire gauge (SWG) for these are 18, 18, 18, 18, 18, 18, 18, 18, 18, 18, 18, 18 and 20, respectively. The number of turns for various windings of transformer T$_{BC}$ (1082.5 VA) are 8, 8, 91.5, 109.5, 61.5, 114.5, 148, 148, 114.5, 61.5, 109.5, 91.5, 539.5 and SWG for these are 18, 18, 18, 18, 18, 18, 18, 18, 18, 18, 18, 18 and 20, respectively. The number of turns for various windings of transformer T$_{CA}$ (1091.5 VA) are 61.5, 109.5, 91.5, 8, 8, 91.5, 109.5, 61.5, 114.5, 148, 148, 114.5, 539.5 and SWG for these are 18, 18, 18, 18, 18, 18, 18, 18, 18, 18, 18, 18 and 20, respectively.

IPT: 28.34 VA; Core size: E-Laminations: Length= 13.35 cm, Width= 8.9 cm; I-Laminations: Length= 13.35 cm, Width= 2.25 cm. Number of turns: 24, 24, 24, 24; SWG: 16, 16, 16, and 16.

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