

Reduced Rating 30-pulse AC-DC Converter for Power Quality Improvement

Rohollah Abdollahi

Department of Electrical Engineering, Technical and Vocational University (Qom Boys Technical College), Qom, Iran

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ABSTRACT

This paper presents the design and analysis of a novel polygon connected autotransformer based 30-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 three paralleled 10-pulse ac-dc converters each of them consisting of 5-phase diode bridge rectifier. An autotransformer is designed to supply the rectifiers. The proposed converter requires only three inter-phase transformers in the dc link that leads to the reduced kilovolt ampere rating, size, weight, and cost of the proposed 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 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 and proposed converters from view point of power quality indices. Results show that input current Total Harmonic Distortion (THD) is less than 3% for the proposed topology at variable loads.

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Corresponding Author:

Rohollah Abdollahi,

Department of Electrical Engineering,

Technical and Vocational University (Qom Boys Technical College), Qom, Iran.

Email: rohollah.abdollahi@yahoo.com, rabdollahi@tvu.ac.ir

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 vector-controlled strategy in that it offers better performance rather than the other control techniques. Vector-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 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

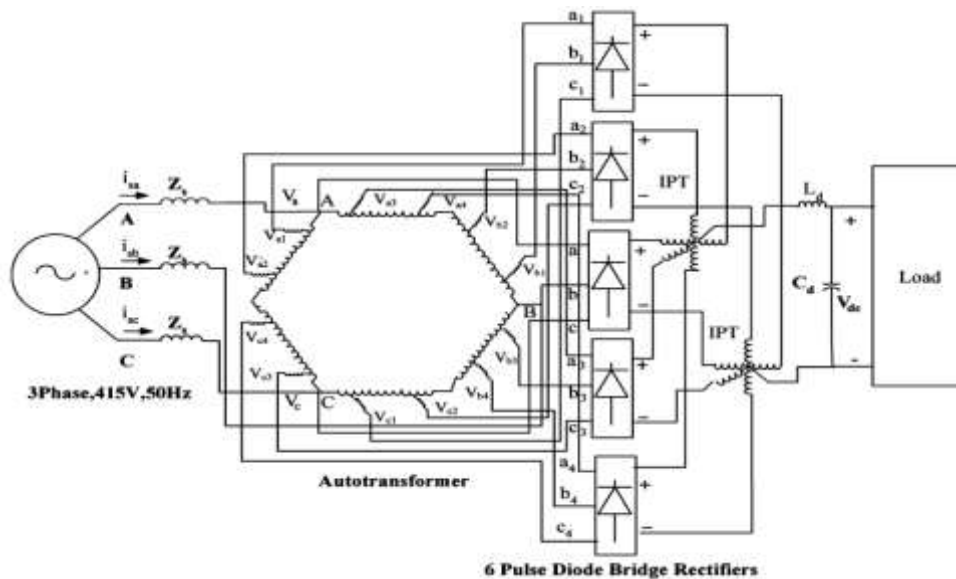
converters. These converters are based on either phase multiplication or phase shifting or pulse doubling or a combination [4-10]. Although, in the conditions of light load or small source impedance, line current Total Harmonic Distortion (THD) will be more than 5% for up to 24-pulse AC-DC converters [10-20].

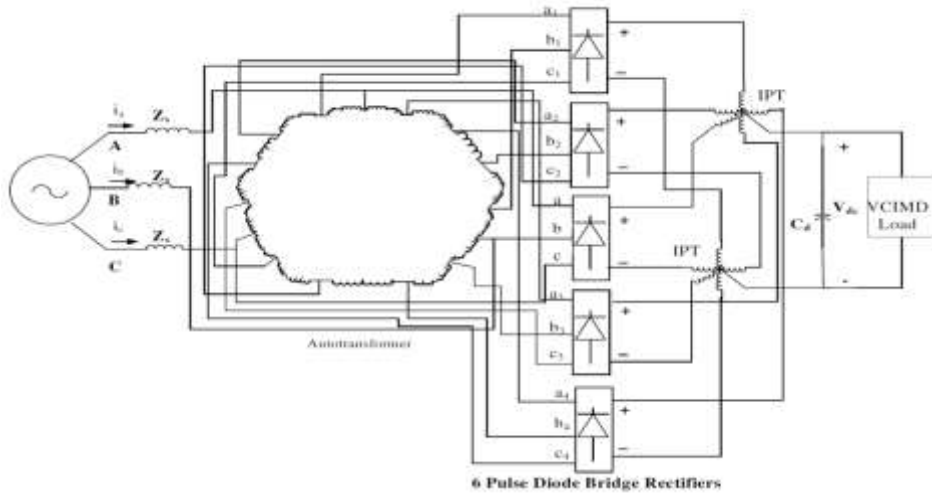
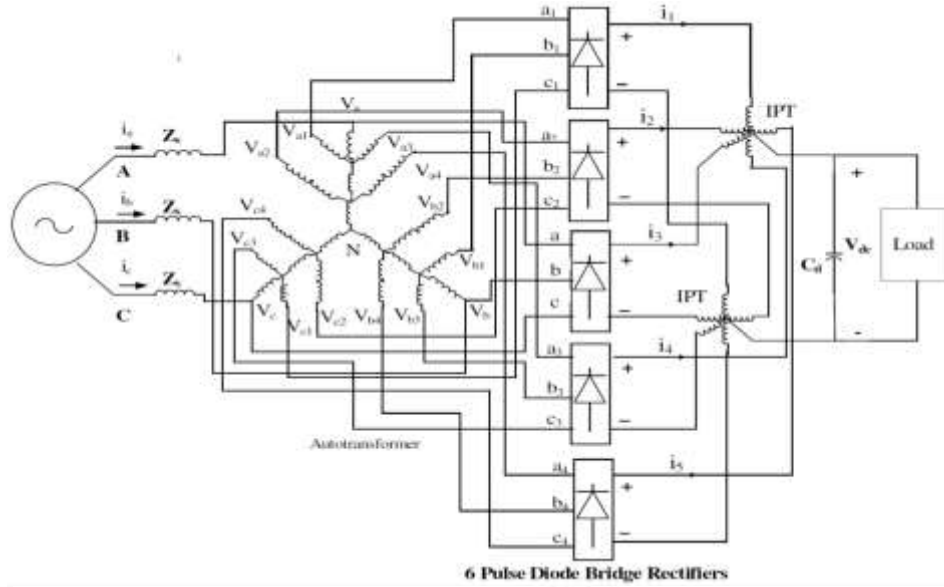
A T-connected Auto Transformer-based 24-Pulse AC-DC Converter has also been presented in [18], however, the THD of the supply current with this topology is reported to vary from 2.46% to 5.20% which is more than 5% when operating at light load. The 36-pulse was designed for VCIMD's in [21] which has THD variation of 2.03% to 3.74% from full-load to light-load (20% of full-load) respectively.

Increasing the number of pulses further results in improvement in various power-quality indexes but along with the additional cost of different converters and increased system complexity [22-24], [26-29]. Therefore, it is suggested that higher pulse configuration with less complexity must be used, so that the ac-dc conversion meets the IEEE-519 requirements. The 40-pulse topology [25] was designed for VCIMD's loads having a THD variation of 2.23% to 3.85% from full-load to light-load (20% of full-load) respectively which is more than 3% when operating at light load, and the dc link voltage is higher than that of a 6-pulse diode bridge rectifier, thus making the scheme nonapplicable for retrofit applications. However, some applications need strict power quality specifications and therefore the usage of converters with pulses more than 24 is unavoidable.

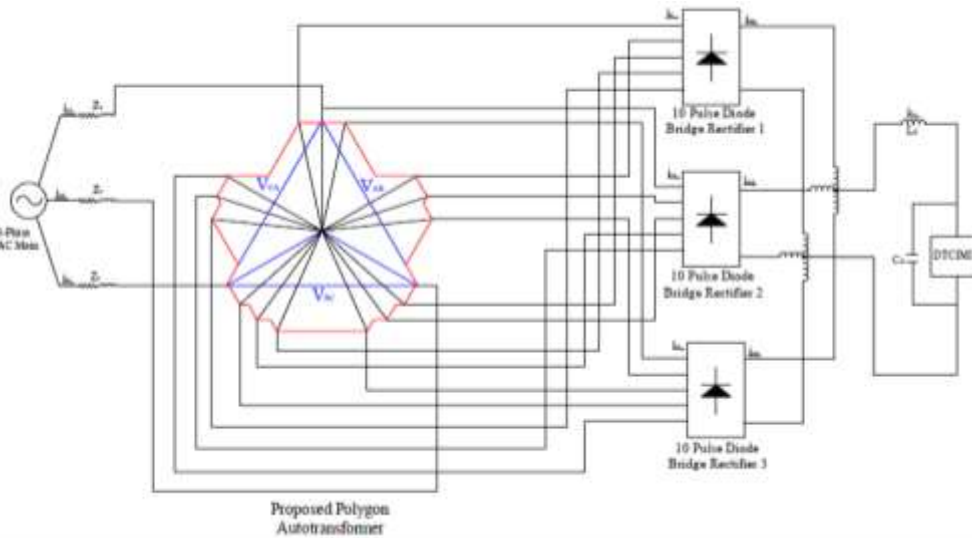
Power quality can be improved by employing passive or active filters [32-39]. Passive filters cause additional losses, need additional floor area and are complex in design as their performance is affected by changes in frequency. Similarly, active filters are also costly and complex, and have ratings comparable to the load rating. The use of multipulse AC-DC converters is one such technique for harmonic mitigation and is found to be rugged and reliable. Various autotransformer based 30-pulse ac-dc converters are introduced in [40]-[42] which has 5 inter-phase transformers in the dc link (Figure 1(a)). In this paper, a 30-pulse ac-dc converter is proposed employing a novel polygon autotransformer as shown in Figure 1(b).

As a result, the proposed converter requires only three inter-phase transformers in the dc link that yields in the reduced kilovolt ampere rating, size, weight, and cost of the proposed rectifier. The proposed design method will be suitable even when the transformer output voltages vary while keeping its 30-pulse operation. In the proposed structure, three 5-leg diode-bridge rectifiers are paralleled via three interphase transformers and fed from an autotransformer. Hence, a 30-pulse output voltage is obtained. Detailed design tips of the IPT and totally the whole structure of 30-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 30-pulse ac-dc converter consisting of a polygon autotransformer, three 10-pulse diode bridge rectifiers paralleled through three IPTs, and with a DTCIMD load Figure 1. Simulation results of six-pulse and proposed 30-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.





(a)



(b)

Figure 1. (a) Another autotransformer configuration for 30-pulse ac–dc conversion (5 inter-phase transformers in the dc link) [40]-[42], (b) Novel polygon-autotransformer configuration for 30-pulse ac–dc conversion (3 inter-phase transformers in the dc link)

2. PROPOSED 30-PULSE AC-DC CONVERTER

In order to implement a 30-pulse ac-dc converter through paralleling three bridge rectifiers, i.e. three 10-pulse rectifiers, three sets of 5-phase voltages with a phase difference of 72 degrees between the voltages of each group and 12 degrees between the same voltages of the three groups are required. Accordingly, each bridge rectifier consists of 5 common-anode and 5 common-cathode diodes (three 5-leg rectifiers). Autotransformer connections and its phasor diagram which shows the angular displacement of voltages are illustrated in Figure 2.

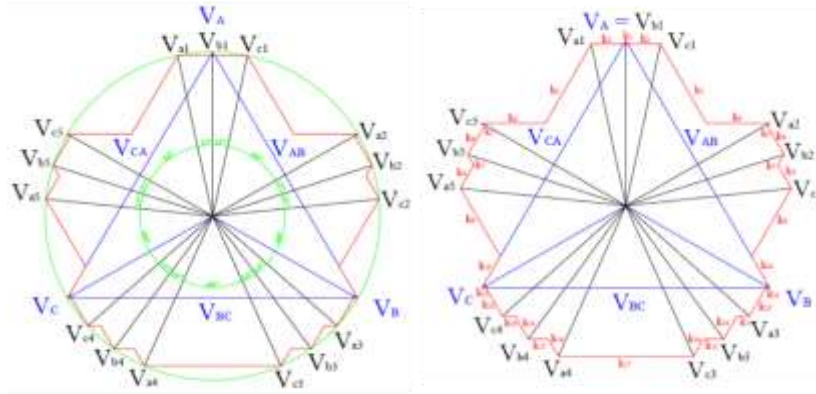


Figure 2. Polygon connection of proposed autotransformer for 30-pulse converter and its phasor representation

2.1. Design of proposed autotransformer for 30-pulse AC-DC converter

The aforementioned three voltage sets are called as $(V_{a1}, V_{a2}, V_{a3}, V_{a4}, V_{a5})$ and $(V_{b1}, V_{b2}, V_{b3}, V_{b4}, V_{b5})$ and $(V_{c1}, V_{c2}, V_{c3}, V_{c4}, V_{c5})$ that are fed to rectifiers I, II and III, respectively. The same voltages of the three groups, i.e. V_{ai} , V_{bi} and V_{ci} , are phase displaced of 12 degrees. V_{b1} and V_{c1} has a phase shift of +12 and -12 degrees from the input voltage of phase A, respectively. According to phasor diagram, the 5-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, 5-phase voltages are:

$$\begin{aligned} V_{a1} &= V_s \angle +12^\circ, V_{a2} = V_s \angle -60^\circ, V_{a3} = V_s \angle -132^\circ, \\ V_{a4} &= V_s \angle -204^\circ, V_{a5} = V_s \angle -276^\circ \end{aligned} \quad (2)$$

$$\begin{aligned} V_{b1} &= V_s \angle 0^\circ, V_{b2} = V_s \angle -72^\circ, V_{b3} = V_s \angle -144^\circ, \\ V_{b4} &= V_s \angle -216^\circ, V_{b5} = V_s \angle -288^\circ \end{aligned} \quad (3)$$

$$\begin{aligned} V_{c1} &= V_s \angle -12^\circ, V_{c2} = V_s \angle -84^\circ, V_{c3} = V_s \angle -156^\circ, \\ V_{c4} &= V_s \angle -228^\circ, V_{c5} = V_s \angle -300^\circ \end{aligned} \quad (4)$$

Input voltages for converter I are:

$$\begin{aligned} V_{a1} &= V_A + K_1 V_{CA} - K_2 V_{BC} \\ V_{a2} &= V_{C1} - K_3 V_{AB} + K_4 V_{BC} \\ V_{a3} &= V_B - K_{11} V_{BC} + K_{12} V_{CA} \\ V_{a4} &= V_{C3} + K_{17} V_{BC} \\ V_{a5} &= V_C - K_{10} V_{CA} + K_9 V_{AB} \end{aligned} \quad (5)$$

Input voltages for converter II are:

$$\begin{aligned}
 V_{b1} &= V_A \\
 V_{b2} &= V_{A2} + K_5 V_{CA} - K_6 V_{AB} \\
 V_{b3} &= V_{A3} - K_{13} V_{BC} + K_{14} V_{CA} \\
 V_{b4} &= V_{A4} + K_{15} V_{AB} - K_{16} V_{BC} \\
 V_{b5} &= V_{A5} - K_8 V_{CA} + K_7 V_{AB}
 \end{aligned}
 \tag{6}$$

Input voltages for converter III are:

$$\begin{aligned}
 V_{a1} &= V_A - K_1 V_{AB} + K_2 V_{BC} \\
 V_{a2} &= V_{B2} + K_7 V_{CA} - K_8 V_{AB} \\
 V_{a3} &= V_{B3} - K_{15} V_{BC} + K_{16} V_{CA} \\
 V_{a4} &= V_{B4} + K_{14} V_{AB} - K_{13} V_{BC} \\
 V_{a5} &= V_{B5} - K_6 V_{CA} + K_5 V_{AB}
 \end{aligned}
 \tag{7}$$

$$V_{AB} = \sqrt{3}V_A \angle 30^\circ, V_{BC} = \sqrt{3}V_B \angle 30^\circ, V_{CA} = \sqrt{3}V_C \angle 30^\circ.
 \tag{8}$$

Constants K_1 - K_{17} are calculated using (2)-(8) to obtain the required windings turn numbers to have the desired phase shift for the three voltage sets:

$$\begin{aligned}
 K_1 &= 0.0145, K_2 = 0.1127, K_3 = 0.3187, K_4 = 0.2205, \\
 K_5 &= 0.0145, K_6 = 0.1127, K_7 = 0.0430, K_8 = 0.0932, \\
 K_9 &= 0.2757, K_{10} = 0.1273, K_{11} = 0.0145, K_{12} = 0.1127, \\
 K_{13} &= 0.0430, K_{14} = 0.0932, K_{15} = 0.0696, K_{16} = 0.0696, \\
 K_{17} &= 0.4696.
 \end{aligned}
 \tag{9}$$

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 30-pulse converter, the rectified output voltage is 14% 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 Figure 3.

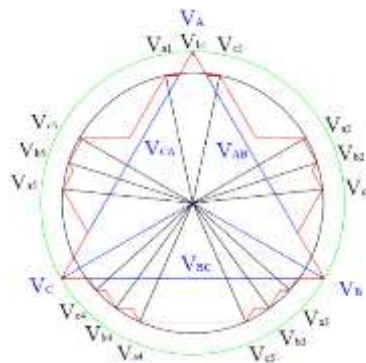


Figure 3. Phasor diagram of voltages in the proposed autotransformer connection along with modifications for retrofit arrangement

It should be noted that with this approach, the desired phase shift is still unchanged. Similar to section 2.1, the following equations can be derived as:

$$|V_S| = 0.86|V_A|
 \tag{10}$$

Applications as:

$$\begin{aligned}
 K_1 &= 0.1058, K_2 = 0.0503, K_3 = 0.2741, K_4 = 0.1896, \\
 K_5 &= 0.0125, K_6 = 0.0970, K_7 = 0.0371, K_8 = 0.0801, \\
 K_9 &= 0.1904, K_{10} = 0.2028, K_{11} = 0.1059, K_{12} = 0.0502, \\
 K_{13} &= 0.0371, K_{14} = 0.0802, K_{15} = 0.0599, K_{16} = 0.0599, \\
 K_{17} &= 0.4038.
 \end{aligned}
 \tag{11}$$

The values of K_1 - K_{17} 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]:

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

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

Figure 4 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 30-pulse converter. The designed autotransformer is modeled via three multi-winding transformers, as shown in Figure 5. Multi-winding transformer block is also used to model IPT. 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 Figures 7-16. Power quality parameters are also listed in Table 1 for 6-pulse and 30-pulse ac-dc converters.

Table 1. The Performance of Comparison of Simulated Power Quality Parameters of The DTCIMD FED From Different AC-DC Converters

Sr. No.	Topology	% THD of V_{ac}	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
1	6-pulse	5.63	0.884	0.959	0.985	0.988	0.872	0.948	616.6	607.9
2	30-pulse	1.94	0.998	0.999	0.995	0.998	0.994	0.997	610.6	606.9

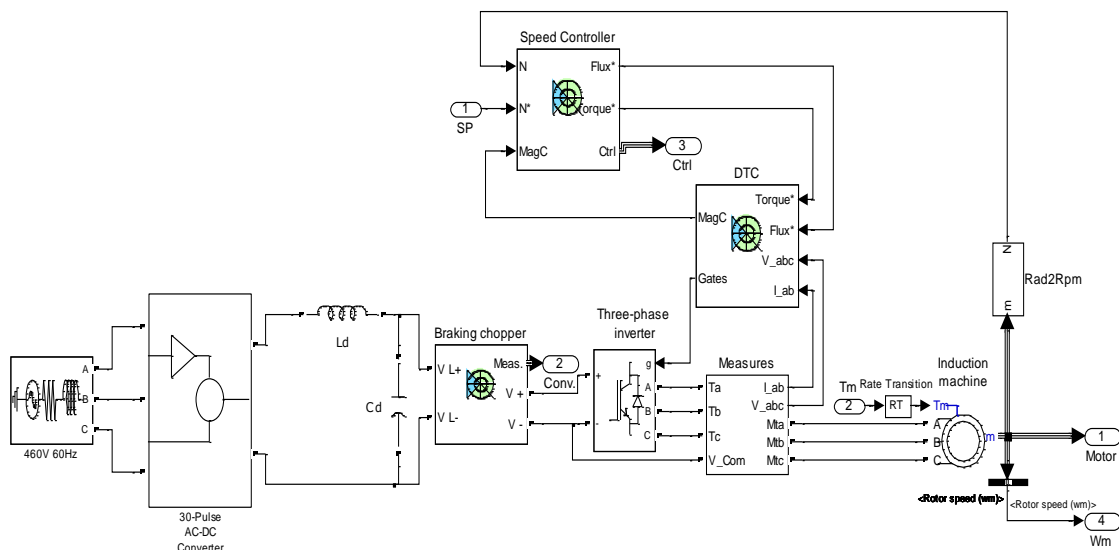


Figure 4. Matlab model of 30-pulse ac-dc converter fed DTCIMD

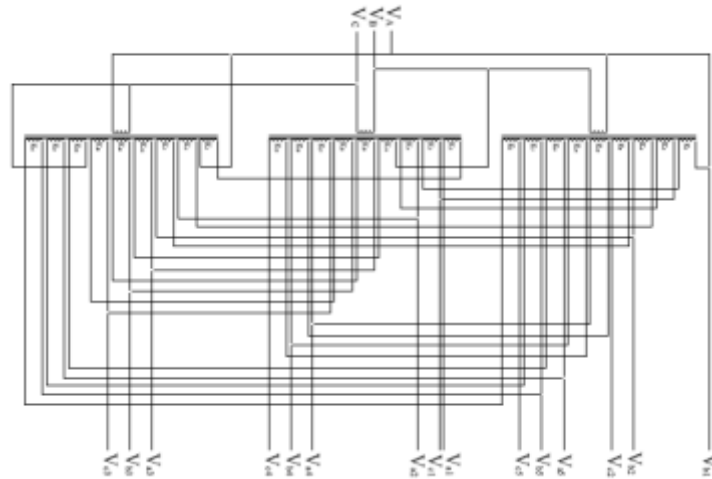


Figure 5. Matlab model of proposed autotransformer for 30-pulse ac–dc converter system simulation

4. RESULTS AND DISCUSSION

Table 1 lists the power quality indices obtained from the simulation results of the 6-pulse and 30-pulse converters. Matlab block diagram of 30-pulse ac–dc converter system simulation, as shown in Figure 6. Figure 7 depicts three groups of 5-phase voltage waveforms with a phase shift of 12 degrees between the same voltages of each group. The voltage across the interphase transformer has a frequency equal to 5 times that of the supply which results in a significant reduction in volume and cost of magnetics. The 30-pulse converter output voltage (shown in Figure 8) is almost smooth and free of ripples and its average value is 609 volts which is approximately equal to the DC link voltage of a six-pulse rectifier (608 volts). This makes the 30-pulse converter suitable for retrofit applications.

Different output and input characteristics of six-pulse and proposed 30-pulse converter feeding DTCIMD such as supply current, rotor speed, electromagnetic torque, and DC link voltage are shown in Figure 9. The dynamic characteristics of the two converters can be used to compare their dynamic response through conditions such as starting or load variations. Input current waveforms and its harmonic spectrum of the 6-pulse and 30-pulse converters extracted and shown in Figures 10-11, respectively to check their consistency with the limitations of the IEEE standard 519. In general, the largely improved performance of the 30-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 two types of converters.

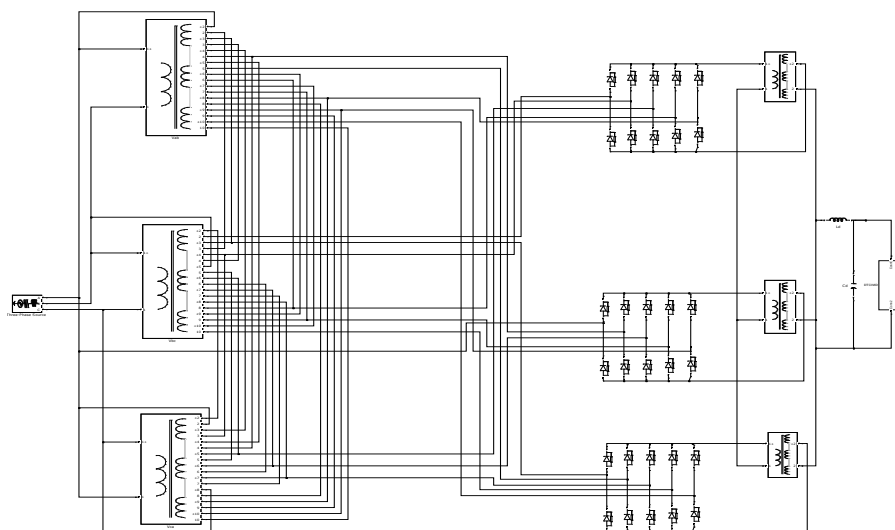


Figure 6. Matlab block diagram of 30-pulse ac–dc converter system simulation

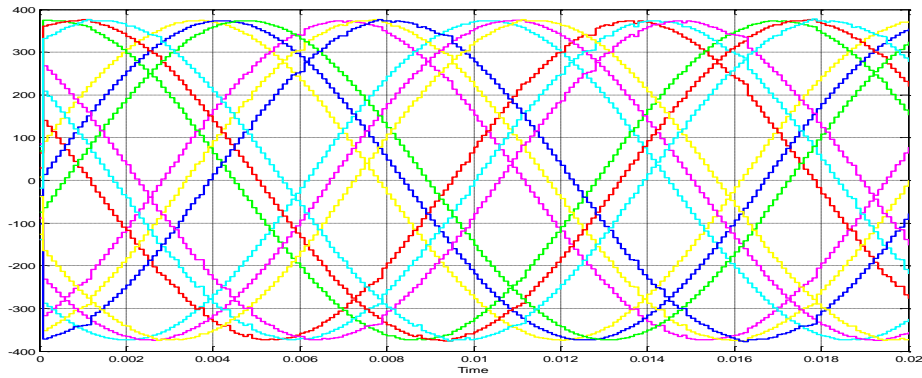


Figure 7. Autotransformer output voltage (three groups of 5-phase voltage)

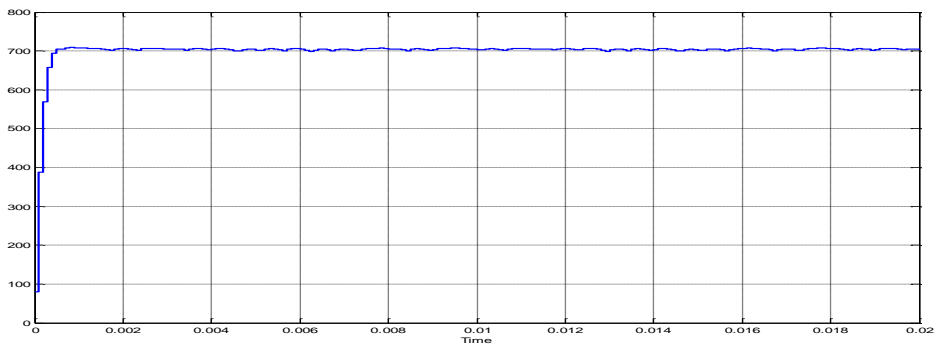


Figure 8. 30-pulse ac-dc converter output voltage

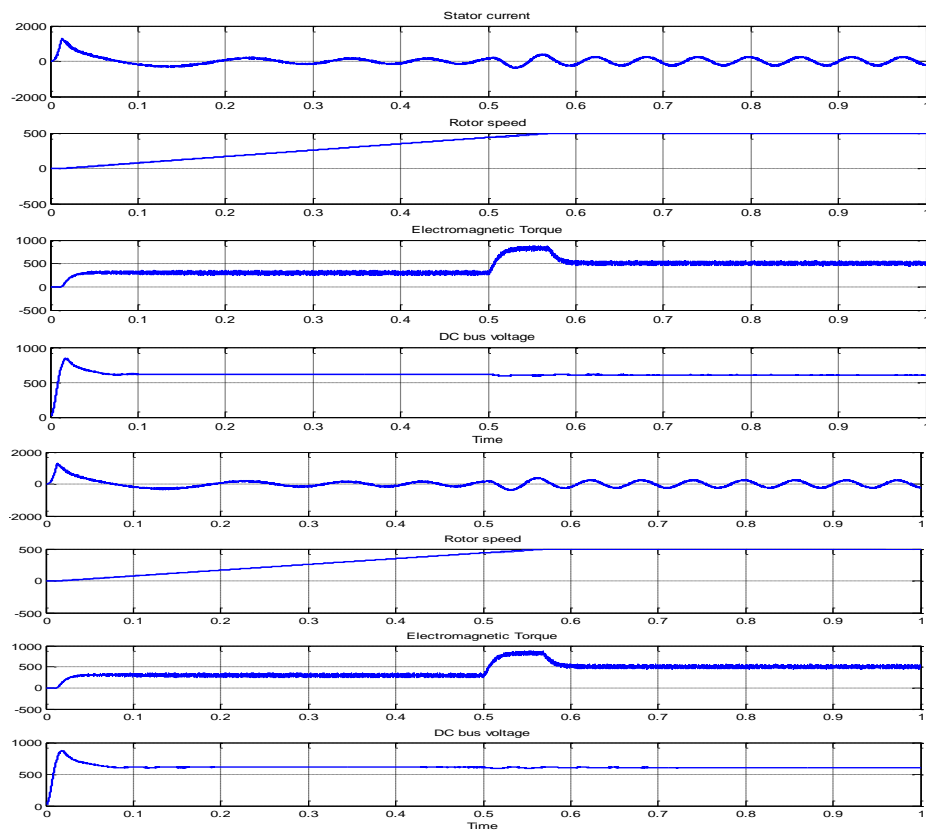


Figure 9. Waveforms depicting dynamic response of 6- and 30-pulse diode rectifier fed DTCIMD with load perturbation (source current i_{sA} , speed ω_r , developed electromagnetic torque T_e , and dc-link voltage V_{dc})

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 52.53% for full load and light load conditions that are not within the standard margins. On the other hand, as shown in Figure 11, 30-pulse converter has an acceptable current THD (3.12% for light load and 2.27% for full load conditions). In this configuration, low order harmonics up to 27th are eliminated in the supply current.

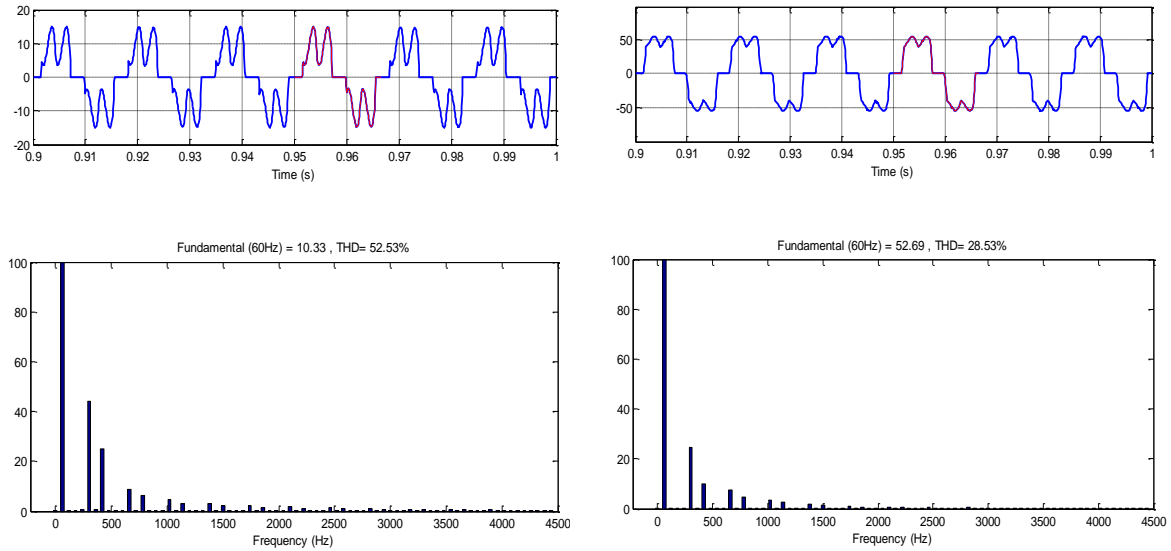


Figure 10. Input current waveform of six-pulse ac–dc converter and its harmonic spectrum at light load and full load

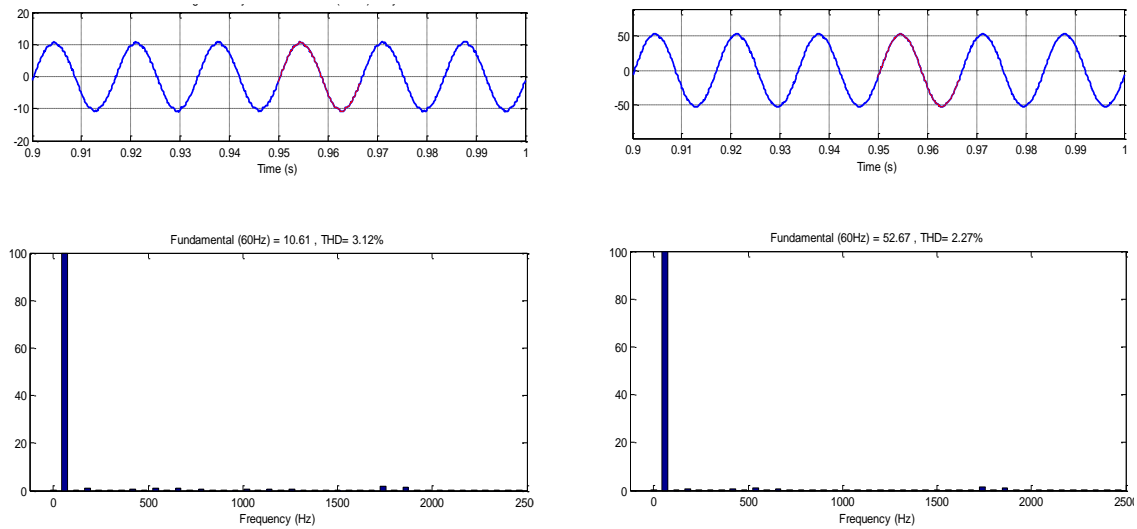


Figure 11. Input current waveform of 30-pulse ac–dc converter and its harmonic spectrum at light load and full load

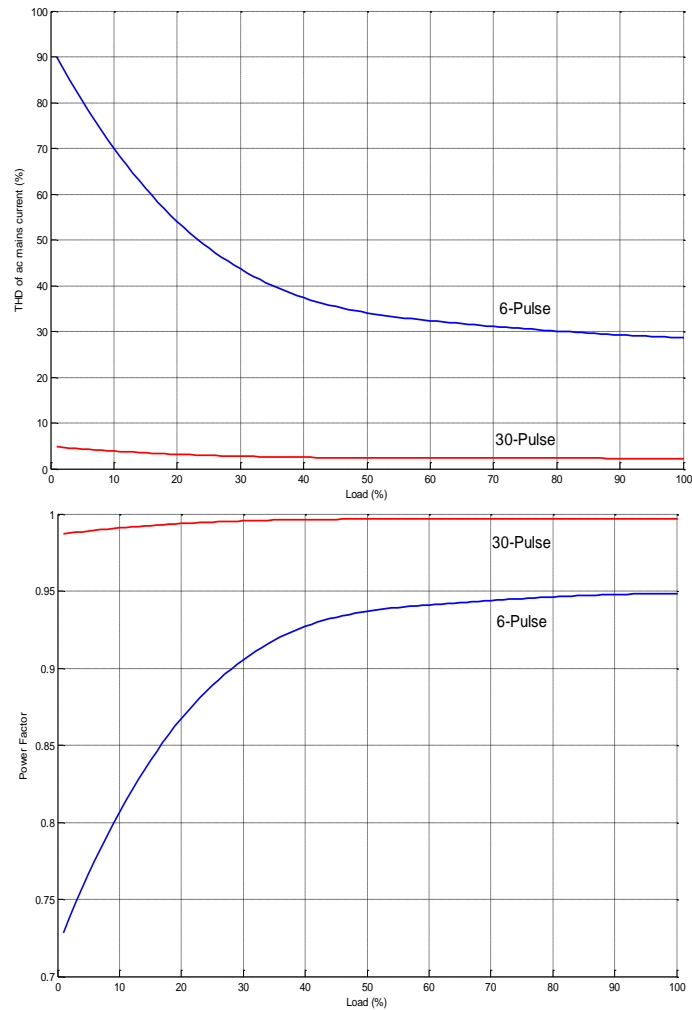


Figure 12. Variation of THD and power factor with load on DTCIMD in 6-pulse and 30-pulse ac-dc converter

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 30-pulse converter has an improved performance and the current THD is always less than 3% for all loading conditions. Input current THD and power factor variations are also shown in Figure 12, for 6-pulse, and 30-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 3% for the proposed topology. Furthermore, the proposed converter requires three inter-phase transformers in the dc link. Compared to other converters that need five IPT that leads to the reduced kilovolt ampere rating, size, and weight of the proposed rectifier. The calculated ratings are 2792.5 VA [40], 2808.3 [41], and 2802.5 [42] for IPT, which are 7.48, 7.52% and 7.51% of the load power rating (37.3kW), respectively. This topology needs an interphase transformer of 1790.4 VA which is 4.8% of the load power rating. The proposed autotransformer-based 30-pulse ac-dc converter results in a cost-effective replacement for retrofit applications, where presently a six-pulse diode bridge rectifier is being used.

Table 2. Comparison of Power Quality Indices of Proposed 30-pulse AC-DC Converter

Load (%)	THD (%)		CF of IS	DF	DPF	PF	RF (%)	V _{dc} (V)
	IS	VS						
20	3.12	0.60	1.412	0.9985	0.9953	0.9938	0.002	610.6
40	2.48	0.78	1.413	0.9988	0.9976	0.9964	0.001	609.7
60	2.35	1.00	1.413	0.9989	0.9978	0.9967	0.003	608.8
80	2.30	1.44	1.413	0.9988	0.9981	0.9968	0.003	607.9
100	2.27	1.94	1.413	0.9988	0.9980	0.9968	0.002	606.9

5. CONCLUSION

A novel polygon-connected autotransformer was designed and modeled to make a 30-pulse ac-dc converter with DTCIMD load. The proposed configuration requires three IPT, which is more economical (in weight, size and kilovolt ampere rating) as compared with other topologies using five IPT. Afterwards, the proposed design procedure was modified for retrofit applications. Simulation 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 3% 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 30-pulse ac-dc converter.

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APPENDIX

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. $R_s=0.0148 \Omega$; $R_r=0.0092 \Omega$; $X_{ls}=1.14\Omega$; $X_{lr}=1.14 \Omega$, $X_{Lm}=3.94 \Omega$, $J=3.1 \text{ Kg} \cdot \text{m}^2$. Controller parameters: PI controller $K_p=300$; $K_i=2000$. DC link parameters: $L_d=2 \text{ mH}$; $C_d=3200 \mu\text{F}$. Source impedance: $Z_s=j0.1884 \Omega$ (=3%).