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T-Connected Autotransformer Based 36-Pulse AC-DC Converter for Power Quality Improvement

***Abstract**. This paper presents the design and analysis of a T-Connected autotransformer based 36-pulse 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 18-pulse ac-dc converters. An autotransformer is designed to supply the rectifiers. The T-connected autotransformer makes use of only two single-phase transformers, resulting in savings in space, volume, weight, and, finally, the cost of the drive. 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 4% for the proposed topology at variable loads.*

***Streszczenie.** W pracy zaprezentowano projekt i analizę 36-pulsowego przekształtnika AD-DC bazującego na autotransformatorze typu T i zasilającego bezpośrednio silnik indukcyjny ze sterowanym momentem obrotowym DTCIMD. Układ wykorzystuje tylko dwa jednofazowe transformatory. Układ zapewnia odpowiednią jakość energii zgodnie z normą IEEE-519. Porównano układ z układem 6-pulsowym. (**36-pulsowy przekształtnik AS-DC z autotransformatorem typu T**)*

Keywords: AC/DC converter, T-Connected autotransformer, power quality, 36-pulse rectifier, direct torque controlled induction motor drive.
Słowa kluczowe: przekształtnik AC-DC, jakość energii, autotransformator.

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]-[8]. 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 18-pulse AC-DC converters [9]-[19]. A Polygon-Connected Autotransformer-Based 24-pulse AC-DC converter is reported in [20] which has THD variation of 4.48% to 5.65% 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 [21], 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.

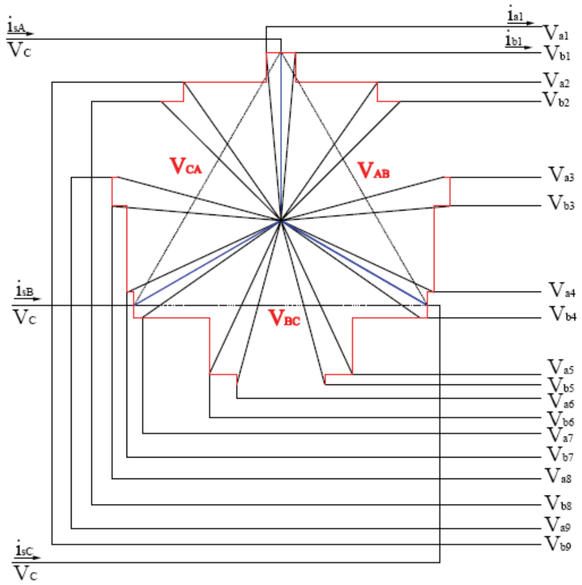

Fig. 1. Proposed autotransformer winding arrangement having T-Connected connection.

However, some applications need strict power quality specifications and therefore the usage of converters with pulses more than 24 is unavoidable. For instance, in some military applications, harmonics are distinguished as signatures by sonar, and unintentionally are coupled capacitively to a ship's hull resulting in induced hull currents that makes the systems such as degaussing equipment malfunction [24].

The Polygon-Connected Autotransformer-Based 36-pulse was designed for VCIMD's in [25] which has THD variation of 2.03% to 3.74% from full-load to light-load (20% of full-load) respectively, but it results in a higher dc-link voltage than that of a 6-pulse diode-bridge rectifier, making the scheme nonapplicable for retrofit applications.

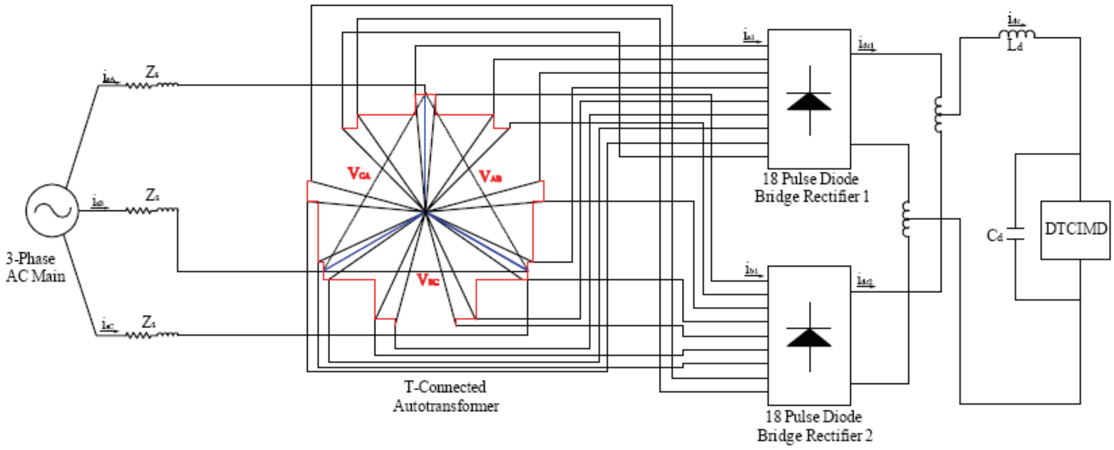

Fig. 2. T-Connected -autotransformer configuration for 36-pulse ac–dc conversion.

In this paper, a 36-pulse ac-dc converter is proposed employing a novel T-Connected autotransformer as shown in Fig. 1. The Polygon-Connected Autotransformer makes use of three single-phase transformers but the T-connected autotransformer makes use of only two single-phase transformers, resulting in savings in space, volume, weight, and, finally, the cost of the drive [17], [21]. 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 9-leg diode-bridge rectifiers are paralleled via two interphase transformers 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 T-Connected autotransformer, two 18-pulse diode bridge rectifiers paralleled through two IPTs, and with a DTCIMD load Fig. 2. Simulation results of six-pulse and proposed 36-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.

Proposed 36-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 9-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 9 common-anode and 9 common-cathode diodes (two 9-leg rectifiers). Autotransformer connections and its phasor diagram which shows the angular displacement of voltages are illustrated in Fig. 3.

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 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:

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

Where, nine-phase voltages are:

(2)
$$\begin{aligned} &V_{a1} = V_s\angle +5^\circ, V_{a2} = V_s\angle -35^\circ, V_{a3} = V_s\angle -75^\circ,\\ &V_{a4} = V_s\angle -115^\circ, V_{a5} = V_s\angle -155^\circ, V_{a6} = V_s\angle -195^\circ,\\ &V_{a7} = V_s\angle -235^\circ, V_{a8} = V_s\angle -275^\circ, V_{a9} = V_s\angle -315^\circ. \end{aligned}$$

(3)
$$\begin{aligned} &V_{b1} = V_s\angle -5^\circ, V_{b2} = V_s\angle -45^\circ, V_{b3} = V_s\angle -85^\circ,\\ &V_{b4} = V_s\angle -125^\circ, V_{b5} = V_s\angle -165^\circ, V_{b6} = V_s\angle -205^\circ,\\ &V_{b7} = V_s\angle -245^\circ, V_{b8} = V_s\angle -285^\circ, V_{b9} = V_s\angle -325^\circ. \end{aligned}$$

Input voltages for converter I are:

(4)
$$\begin{aligned} V_{a1} &= V_A - K_1 V_A - K_2 V_{BC}\\ V_{a2} &= V_{b1} - K_3 V_A + K_4 V_{BC}\\ V_{a3} &= V_{b3} + K_8 V_A - K_7 V_{BC}\\ V_{a4} &= V_B + K_{12} V_A + K_{11} V_{BC}\\ V_{a5} &= V_{b4} - K_{16} V_A - K_{15} V_{BC}\\ V_{a6} &= V_{b6} - K_{18} V_A + K_{17} V_{BC}\\ V_{a7} &= V_C - K_{13} V_A + K_{14} V_{BC}\\ V_{a8} &= V_{b7} + K_{10} V_A - K_9 V_{BC}\\ V_{a9} &= V_{b9} - K_5 V_A - K_6 V_{BC} \end{aligned}$$

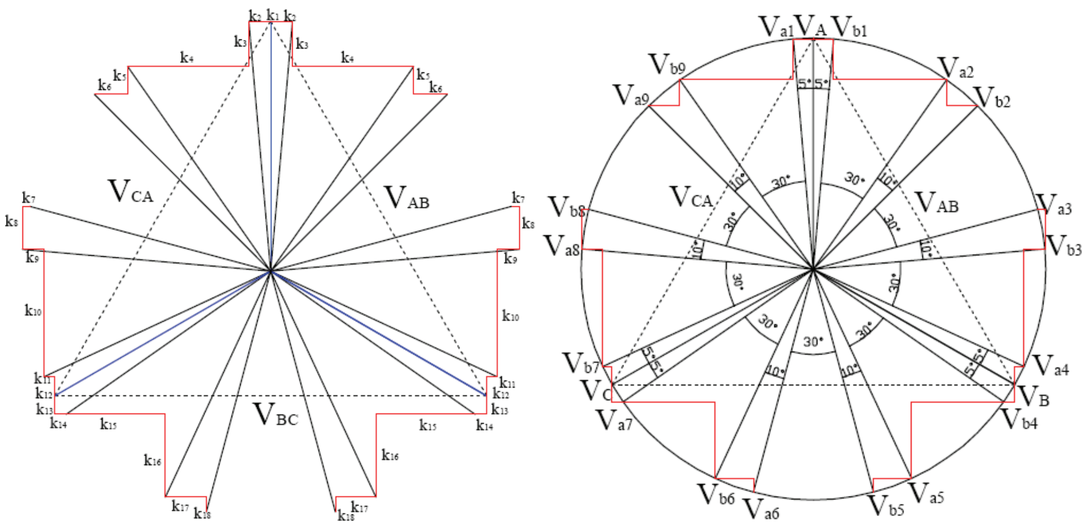

Fig.3. T- connection of proposed autotransformer for 36-pulse converter and its phasor representation.

Input voltages for converter II are:

(5)
$$\begin{aligned}
V_{b1} &= V_A - K_1 V_A + K_2 V_{BC}\\
V_{b2} &= V_{a2} - K_5 V_A + K_6 V_{BC}\\
V_{b3} &= V_{a4} + K_{10} V_A + K_9 V_{BC}\\
V_{b4} &= V_B - K_{13} V_A - K_{14} V_{BC}\\
V_{b5} &= V_{a5} - K_{18} V_A - K_{17} V_{BC}\\
V_{b6} &= V_{a7} - K_{16} V_A + K_{15} V_{BC}\\
V_{b7} &= V_C + K_{12} V_A - K_{11} V_{BC}\\
V_{b8} &= V_{a8} + K_8 V_A + K_7 V_{BC}\\
V_{b9} &= V_{a1} - K_3 V_A - K_4 V_{BC}
\end{aligned}$$

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

Constants K_1-K_{18} are calculated using (2)-(6) to obtain the required windings turn numbers to have the desired phase shift for the two voltage sets:

(7)
$$\begin{aligned}
&K_1 = 0.0038, K_2 = 0.0503, K_3 = 0.17704,\\
&K_4 = 0.28026, K_5 = 0.11205, K_6 = 0.0771,\\
&K_7 = 0.01747, K_8 = 0.17167, K_9 = 0.05189,\\
&K_{10} = 0.50976, K_{11} = 0.02326, K_{12} = 0.07739,\\
&K_{13} = 0.07357, K_{14} = 0.027, K_{15} = 0.22894,\\
&K_{16} = 0.33273, K_{17} = 0.09457, K_{18} = 0.05962.
\end{aligned}$$

Design of Proposed 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 17% 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. 4. It should be noted that with this approach, the desired phase shift is still unchanged. Similar to front section, the following equations can be derived as:

(8)
$$|V_S| = 0.8328\,|V_A|$$

Input voltages for converter I are:

(9)
$$\begin{aligned}
V_{a1} &= V_A - K_1 V_A - K_2 V_{BC}\\
V_{a2} &= V_{b1} - K_3 V_A + K_4 V_{BC}\\
V_{a3} &= V_{b3} + K_8 V_A - K_7 V_{BC}\\
V_{a4} &= V_B + K_{12} V_A - K_{11} V_{BC}\\
V_{a5} &= V_{b4} - K_{16} V_A - K_{15} V_{BC}\\
V_{a6} &= V_{b6} - K_{18} V_A + K_{17} V_{BC}\\
V_{a7} &= V_C + K_{13} V_A + K_{14} V_{BC}\\
V_{a8} &= V_{b7} + K_{10} V_A - K_9 V_{BC}\\
V_{a9} &= V_{b9} - K_5 V_A - K_6 V_{BC}
\end{aligned}$$

Input voltages for converter II are:

(10)
$$\begin{aligned}
V_{b1} &= V_A - K_1 V_A + K_2 V_{BC}\\
V_{b2} &= V_{a2} - K_5 V_A + K_6 V_{BC}\\
V_{b3} &= V_{a4} + K_{10} V_A + K_9 V_{BC}\\
V_{b4} &= V_B + K_{13} V_A - K_{14} V_{BC}\\
V_{b5} &= V_{a5} - K_{18} V_A - K_{17} V_{BC}\\
V_{b6} &= V_{a7} - K_{16} V_A + K_{15} V_{BC}\\
V_{b7} &= V_C + K_{12} V_A + K_{11} V_{BC}\\
V_{b8} &= V_{a8} + K_8 V_A + K_7 V_{BC}\\
V_{b9} &= V_{a1} - K_3 V_A - K_4 V_{BC}
\end{aligned}$$

Accordingly, the values of constants K_1-K_{18} are changed for retrofit applications as:

(11)
$$\begin{aligned}
&K_1 = 0.17037, K_2 = 0.0419, K_3 = 0.14745,\\
&K_4 = 0.23388, K_5 = 0.09331, K_6 = 0.0642,\\
&K_7 = 0.01455, K_8 = 0.14296, K_9 = 0.04322,\\
&K_{10} = 0.42453, K_{11} = 0.06422, K_{12} = 0.14805,\\
&K_{13} = 0.02233, K_{14} = 0.10613, K_{15} = 0.19066,\\
&K_{16} = 0.2771, K_{17} = 0.07875, K_{18} = 0.04965.
\end{aligned}$$

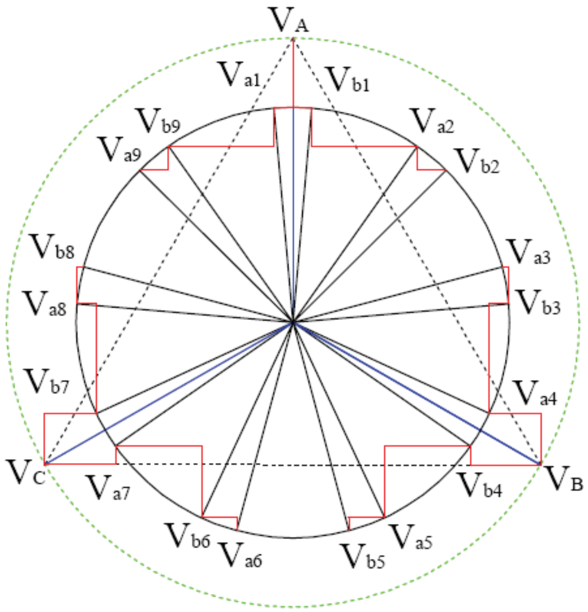

Fig.4. Phasor diagram of voltages in the proposed autotransformer connection alongwith modifications for retrofit arrangement.

The values of K_1-K_{18} establish the essential turn numbers of the autotransformer windings to have the required output voltages and phase shifts. The kilovoltampere rating of the autotransformer is calculated as [4]:

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

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

MATLAB-Based Simulation

Fig. 5 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 36-pulse converter. The designed autotransformer is modeled via three multi-winding transformers. Multi-winding transformer block is also used to model IPT. The ratings of input transformer and IPT are estimated, and these are 61.53%, and 0.32%, respectively of the load rating.

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 vector-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.

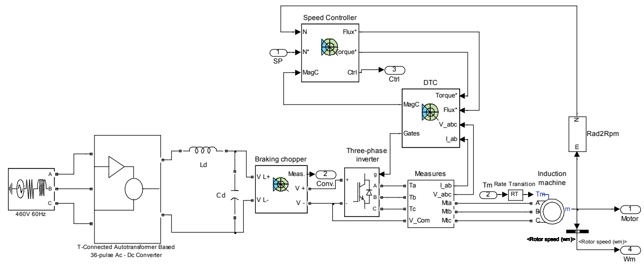

Fig. 5. Matlab model of 36-pulse ac–dc converter fed DTCIMD.

Results and Discussion

Table I lists the power quality indices obtained from the simulation results of the 6-pulse and 36-pulse converters. Matlab block diagram of 36-pulse ac–dc converter system simulation, as shown in Fig. 6. Fig. 7 depicts two groups of 9-phase voltage waveforms with a phase shift of 10 degrees between the same voltages of each group.

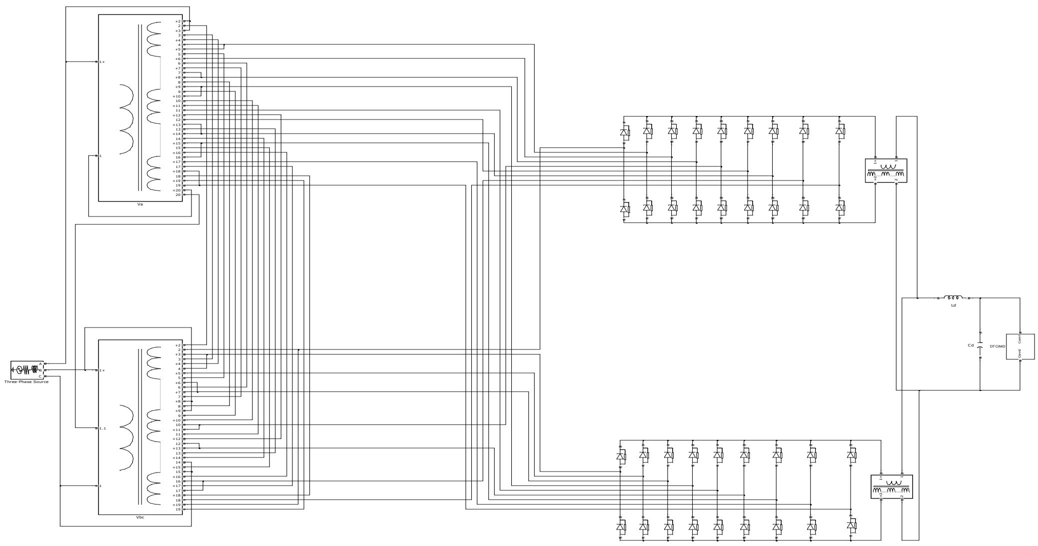

Fig. 6. Matlab block diagram of 36-pulse ac–dc converter system simulation.

The voltage across the interphase transformer (shown in Fig. 8) 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. 9) 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 36-pulse converter suitable for retrofit applications.

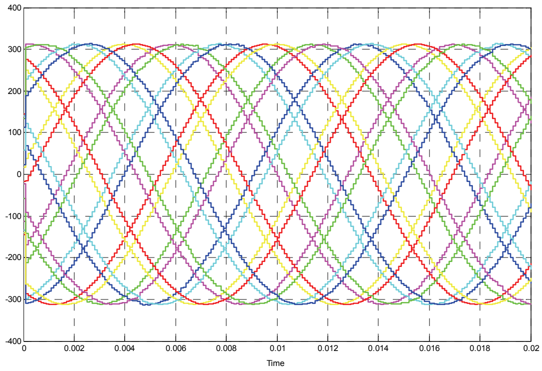

Fig. 7. Autotransformer output voltage.

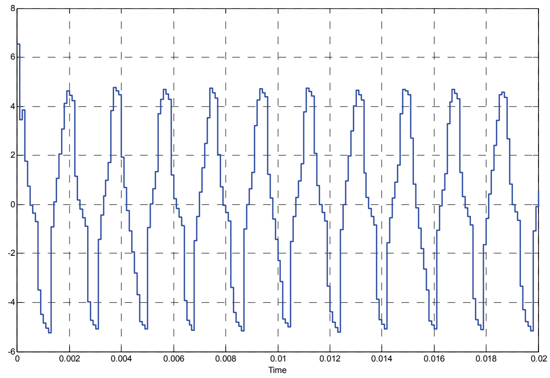

Fig. 8. Voltage waveform across the interphase transformer.

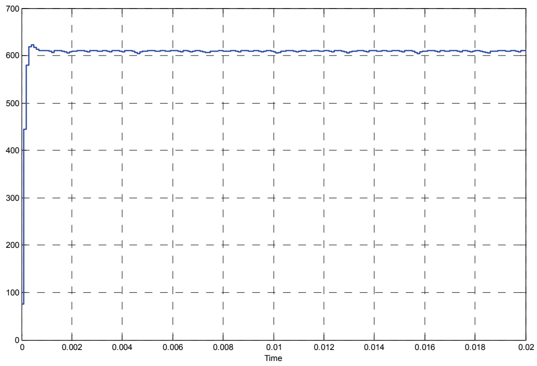

Fig. 9. 36-pulse ac–dc converter output voltage.

Different output and input characteristics of the proposed 36-pulse converter feeding DTCIMD such as supply current, rotor speed, electromagnetic torque, and DC link voltage are shown in Fig. 10. These waveforms can be compared with their equivalent parameters of a six-pulse fed DTCIMD that are shown in Fig. 11. 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-pulseand 36-pulse converters extracted and shown in Figs. 12-15, respectively to check their consistency with the limitations of the IEEE standard 519.

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 I for the three types of converters.

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. 14-15, 36-pulse converter has an acceptable current THD (3.94% for light load and 2.82% for full load conditions). In this configuration, low order harmonics up to 33rd are eliminated in the supply current.

Input current THD and power factor variations are also shown in Figs. 16 and 17 respectively, 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.

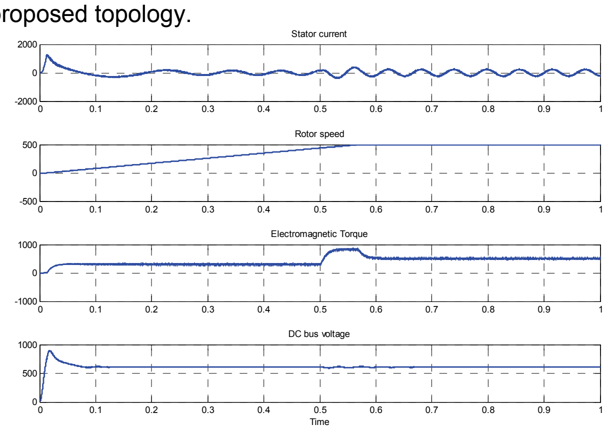

Fig. 10. Waveforms depicting dynamic response of 36-pulse diode rectifier fed DTCIMD with load perturbation (source current i_{sA}, speed ω_r , developed electromagnetic torque T_e , and dc-link voltage V_{dc}).

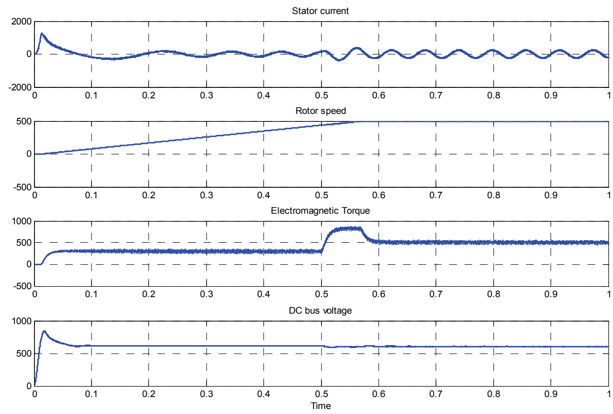

Fig. 11. Waveforms depicting dynamic response of six-pulse diode rectifier fed DTCIMD with load perturbation.

Conclusion

A novel T-connected autotransformer was designed and modeled to make a 36-pulse ac-dc converter with DTCIMD load. The proposed autotransformer makes use of only two single-phase transformers, resulting in saving in space, weight, volume, and the cost. 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 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.

Table I
COMPARISON OF SIMULATED POWER QUALITY PARAMETERS OF THE DTCIMD 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	
			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
2	36-pulse	2.46	10.49	52.21	3.94	2.82	0.9992	0.9993	0.9996	0.9987	0.9987	0.9980

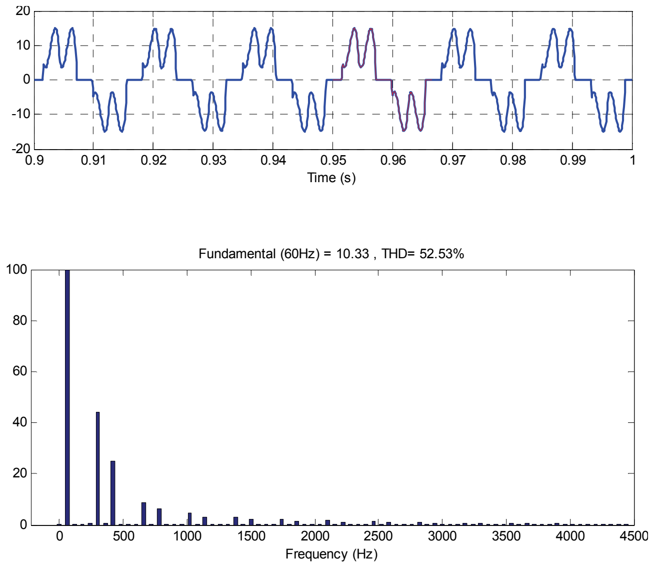

Fig. 12. Input current waveform of six-pulse ac–dc converter at light load and its harmonic spectrum.

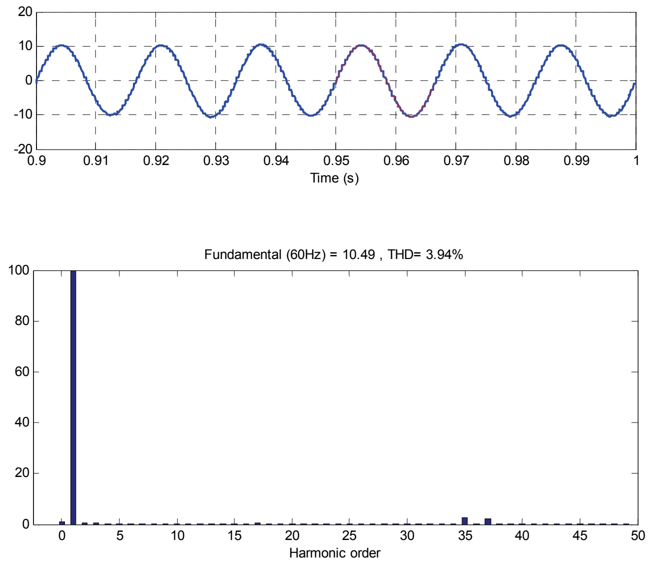

Fig. 14. Input current waveform of 36-pulse ac–dc converter at light load and its harmonic spectrum.

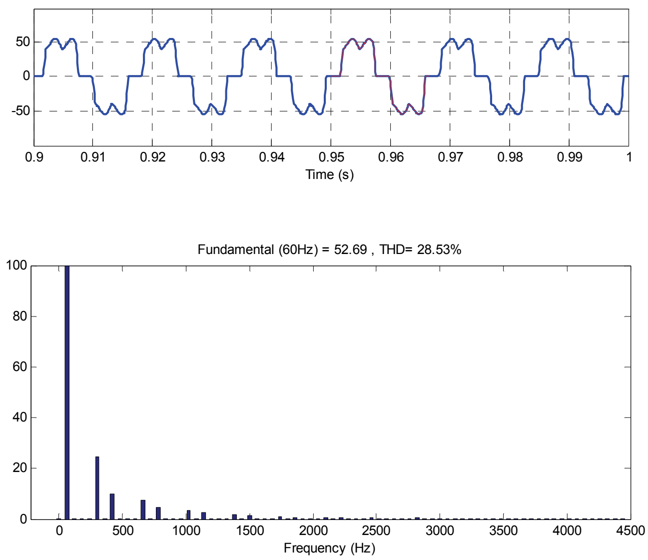

Fig. 13. Input current waveform of six-pulse ac–dc converter at full load and its harmonic spectrum.

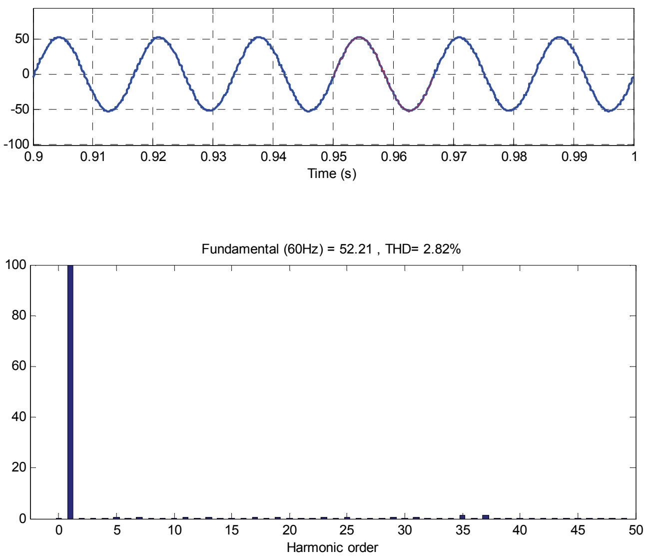

Fig. 15. Input current waveform of 36-pulse ac–dc converter at full load and its harmonic spectrum.

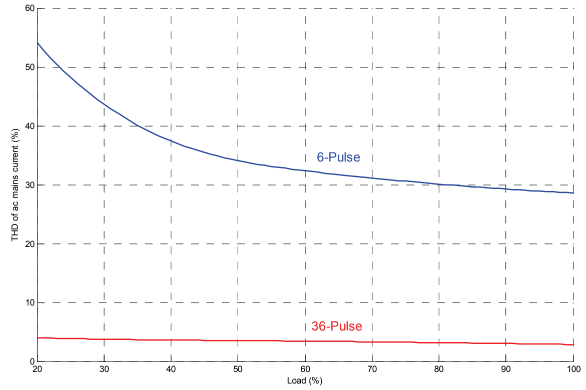

Fig. 16. Variation of THD with load on DTCIMD in 6-pulse and 36-pulse ac-dc converter.

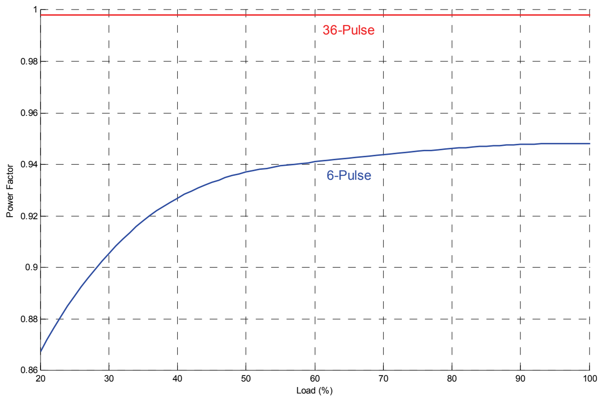

Fig. 17. Variation of power factor with load on DTCIMD in 6-pulse and 36-pulse ac-dc converter.

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 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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