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A Novel Delta/Hexagon-Connected Transformer-Based 72-Pulse AC-DC Converter for Power Quality Improvement

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Abstract: This paper presents a pulse doubling technique in a 36-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 36-pulse rectified output voltage is accomplished via two paralleled eighteen-pulse ac-dc converters each of them consisting of nine-phase diode bridge rectifier. A transformer 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 72 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, 36-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.

Key words: AC–DC converter · Delta/hexagon transformer · Power quality · 72-pulse rectifier · Pulse doubling · Direct torque controlled induction motor drive (DTCIMD)

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]. 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 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 [4-25]. 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.

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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 30-pulse converter and between 2.038% and 3.748% for the 36-pulse converter 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.

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 [16]. Hence, it is critical to avoid the operation of apparatus which produce harmonic components with amplitudes greater that 3% of nominal fundamental component.

In this paper, a 72-pulse ac-dc converter is extracted from a 36-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 36-pulse operation. In the proposed structure, two nine-leg diode-bridge rectifiers are paralleled via a Zero Sequence Blocking Transformer (ZSBT) and fed from a transformer. Hence, a 36-pulse output voltage is obtained. In order to double the number of pulses up to 72, 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]. In other words, the removal of harmonics in 36-pulse converter is accomplished via the dc voltage ripple which is the frequency source for the derivation of adequate voltage and current waveforms. Ratings of IPR are small versus output apparent power. The number of turns in each IPR taps is such that the operation of diodes produces a near sinusoidal waveform in the ac line currents. Detailed design tips of the tapped IPR and totally the whole structure of 72-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 delta/hexagon transformer, two eighteen-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 72-pulse ac-dc converter. Simulation results of six-pulse, 36-pulse and proposed 72-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 72-Pulse AC–DC Converter: The 36-pulse topology is obtained via two paralleled 18-pulse bridge rectifiers (two nine-leg rectifiers) are required. For this purpose, a delta/hexagon autotransformer is designed to produce two sets of nine phase voltages. The 18-phase tapped delta autotransformer generates two sets of nine-phase voltages with a phase difference of 40 degrees between the voltages of each group and 10 degrees difference between the same voltages supply for each bridge. The phasor diagram of the proposed tapped delta autotransformer having two sets of 9-phase voltages with the required angular displacement is illustrated in Fig. 2. The 36-pulse ac–dc converter is extended to 72-pulse ac–dc converter by pulse-doubling technique. Phasor diagram of delta/hexagon transformer is shown in Fig. 3. The hexagon transformer winding arrangement for 36-pulse AC-DC conversion is shown in Fig. 4 and its connection along with phasor diagram.

Design of Proposed Transformer 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:

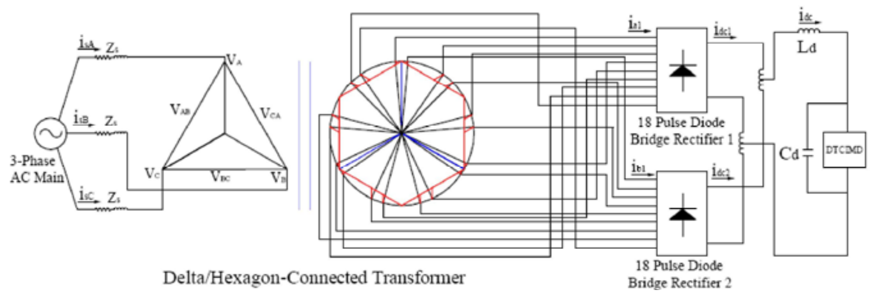

Fig. 1: Delta/hexagon-transformer configuration for 36-pulse ac–dc conversion

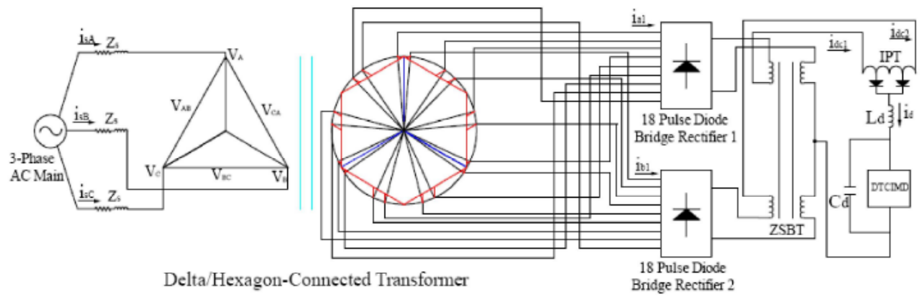

Fig. 2: Delta/hexagon transformer configuration for 72-pulse ac–dc conversion

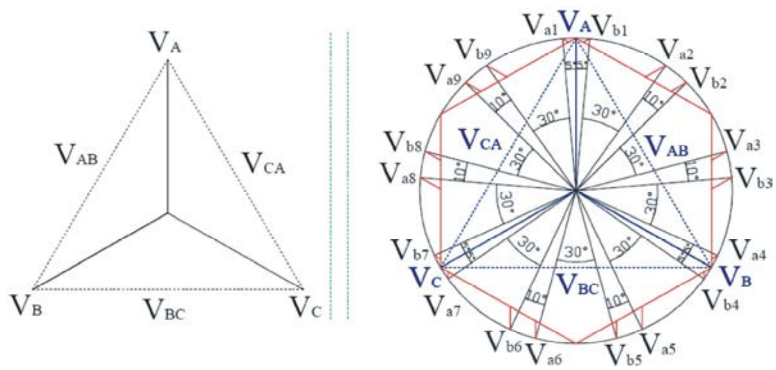

Fig. 3: Phasor representation of transformer for 36-pulse AC-DC converter having Hexagon connected secondary winding

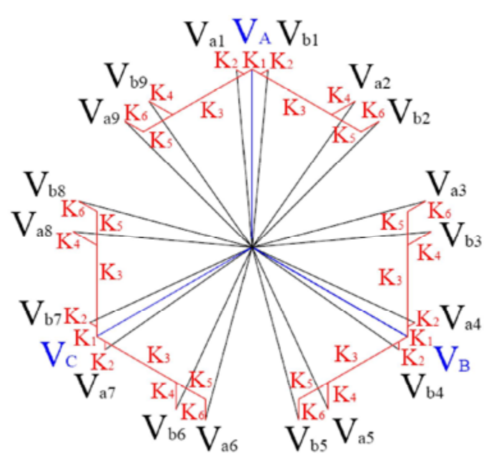

Fig. 4: Winding arrangement of transformer for 36-pulse AC-DC converter having hexagon connected secondary winding

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

Where, nine-phase voltages are:

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

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

Input voltages for converter I are:

$$\begin{aligned}
V_{a1} &= V_A + K_1V_C - K_2V_B\\
V_{a2} &= V_A + K_3V_B - K_4V_C\\
V_{a3} &= V_A - K_5V_A - K_6V_C\\
V_{a4} &= V_B + K_1V_A - K_2V_C\\
V_{a5} &= V_B + K_3V_C - K_4V_A\\
V_{a6} &= V_C + K_5V_B - K_6V_A\\
V_{a7} &= V_C + K_1V_B - K_2V_A\\
V_{a8} &= V_C + K_3V_A - K_4V_B\\
V_{a9} &= V_A + K_5V_C - K_6V_B
\end{aligned} \quad (4)$$

Input voltages for converter II are:

$$\begin{aligned}
V_{a1} &= V_A + K_1V_B - K_2V_C\\
V_{a2} &= V_A + K_5V_B - K_6V_C\\
V_{a3} &= V_B + K_3V_A - K_4V_C\\
V_{a4} &= V_B + K_1V_C - K_2V_A\\
V_{a5} &= V_B + K_5V_C - K_6V_A\\
V_{a6} &= V_C + K_3V_B - K_4V_A\\
V_{a7} &= V_C + K_1V_A - K_2V_B\\
V_{a8} &= V_C + K_5V_A - K_6V_B\\
V_{a9} &= V_A + K_3V_C - K_4V_B
\end{aligned} \quad (5)$$

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

Constants K_1-K_6 are calculated using (2)-(6) to obtain the required windings turn numbers to have the desired phase shift for the two voltage sets:

$K_1 = 0.0511$. $K_2 = 0.04651$, $K_3 = 0.5120$ (7)
$K_4 = 0.1503$, $K_5 = 0.7011$, $K_6 = 0.1153$.

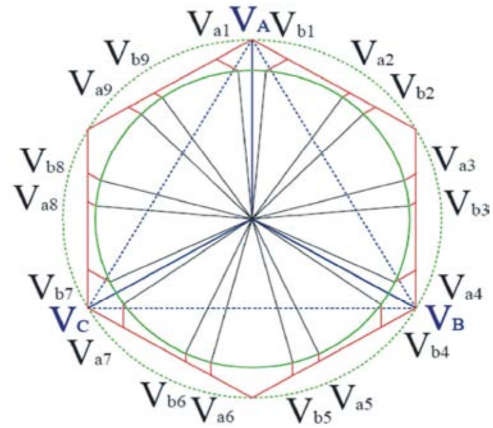

Fig. 5: Phasor diagram of voltages in the proposed transformer connection along with modifications for retrofit arrangement

Design of Transformer 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 transformer arrangement of the proposed 72-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. 5. 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:

$$|V_s| = 0.8314\ |V_A| \quad (8)$$

Input voltages for vonverter I are:

$$\begin{aligned}
V_{a1} &= V_A + K_1V_C + K_2V_B\\
V_{a2} &= V_A + K_3V_B + K_4V_C\\
V_{a3} &= V_A - K_5V_A + K_6V_C\\
V_{a4} &= V_B + K_1V_A + K_2V_C\\
V_{a5} &= V_B + K_3V_C + K_4V_A\\
V_{a6} &= V_C + K_5V_B + K_6V_A\\
V_{a7} &= V_C + K_1V_B + K_2V_A\\
V_{a8} &= V_C + K_3V_A + K_4V_B\\
V_{a9} &= V_A + K_5V_C + K_6V_B
\end{aligned} \quad (9)$$

Input voltages for converter II are:

$$
\begin{aligned}
V_{a1} &= V_A + K_1V_B + K_2V_C \\
V_{a2} &= V_A + K_5V_B + K_6V_C \\
V_{a3} &= V_B + K_3V_A + K_4V_C \\
V_{a4} &= V_B + K_1V_C + K_2V_A \\
V_{a5} &= V_B + K_5V_C + K_6V_A \\
V_{a6} &= V_C + K_3V_B + K_4V_A \\
V_{a7} &= V_C + K_1V_A + K_2V_B \\
V_{a8} &= V_C + K_5V_A + K_6V_B \\
V_{a9} &= V_A + K_3V_C + K_4V_B
\end{aligned} \tag{10}
$$

Accordingly, the values of constants K_1-K_6 are changed for retrofit applications as:

$$
\begin{aligned}
&K_1 = 0.2136,\ K_2 = 0.12994,\ K_3 = 0.59428 \\
&K_4 = 0.04364,\ K_5 = 0.75154,\ K_6 = 0.0727
\end{aligned} \tag{11}
$$

The values of K_1-K_6 establish the essential turn numbers of the transformer windings to have the required output voltages and phase shifts. The kilovoltampere rating of the transformer is calculated as [4]:

$$kVA = 0.5\ \Sigma_{winding}\ I_{winding} \tag{12}$$

where, Vwinding is the voltage across each transformer winding and Iwinding 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.

Interphase Transformer: 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 a 72-pulse current from two paralleled 18-pulse rectifiers. The IPR and tapped diodes are shown in Fig. 6.

For the pulse multiplication process, it is necessary to ensure that the average output voltages of bridges are equal and phase shifted of 10 degrees. As two 18-pulse rectifiers are paralleled, the voltage across the interphase transformer, V_m, has a frequency 18 times that of the supply system. Therefore, size, weight and volume of the transformer reduce relative to rectifiers with a less pulse number.

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 Vm is negative. The MMF equivalence between the windings when D_1 is on yields:

$$i_{dc1}\ N_A = i_{dc2}\ N_B \tag{13}$$

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

$$i_{dc1} + i_{dc2} = i_{dc} \tag{14}$$

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

$$i_{dc1} = (0.5 + K_t)i_{dc} \qquad i_{dc2} = (0.5 + K_t)i_{dc} \tag{15}$$

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.

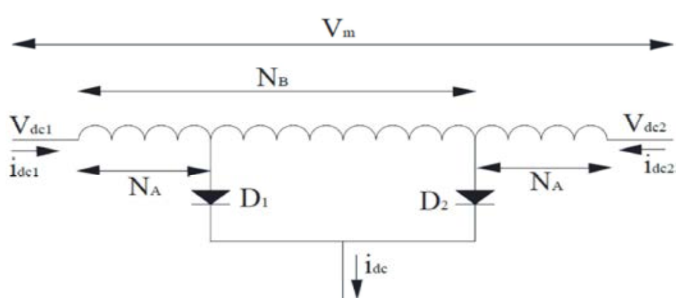

Fig. 6: Tapped Inter-phase Transformer circuit

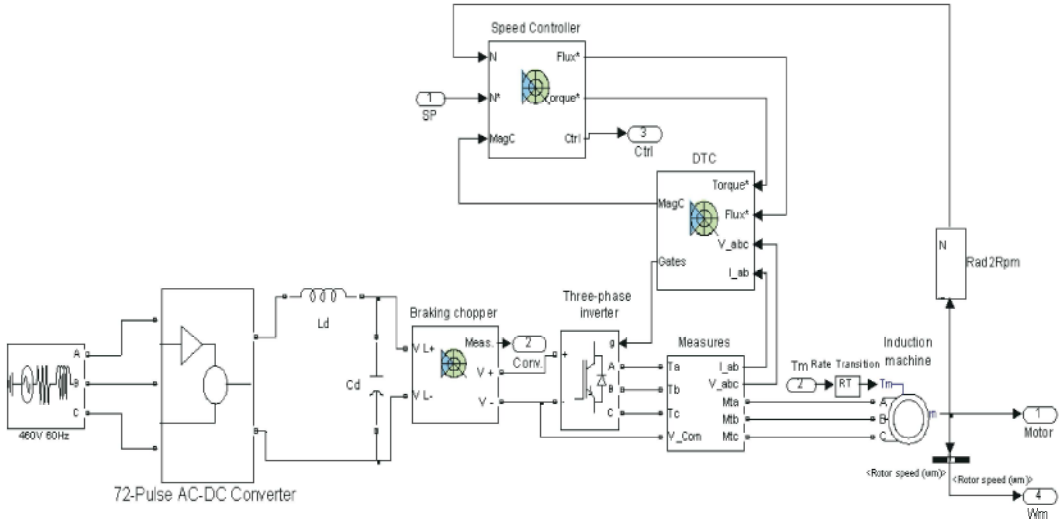

Fig. 7: Matlab model of 72-pulse ac–dc converter fed DTCIMD

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 72-pulse converter, the voltage frequency of ZSBT is nine times that of the supply system and consequently it shows high impedance nine 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.

Matlab-Based Simulation: Fig. 7 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 72-pulse converter. The designed transformer is modeled via three multi-winding transformers. Multi-winding transformer block is also used to model ZSBT and IPT.

At the converter output, a series inductance (L) and a parallel capacitor © 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. Simulation results are depicted in Figs. 8-23. Power quality p arameters are also listed in Table 1 for 6-pulse, 36-pulse and 72-pulse ac-dc converters.

RESULTS AND DISCUSSION

Table 1 lists the power quality indices obtained from the simulation results of the 6-pulse, 36-pulse and 72-pulse converters. MATLAB block diagram of 72-pulse ac–dc converter system simulation, as shown in Fig. 8. Fig. 9 depicts two groups of nine-phase voltage waveforms with a phase shift of 10 degrees between the same voltages of each group. Output voltage waveforms of the two parallel 18-pulse rectifiers with a phase difference of 10 degrees are shown in Fig. 10.

Diode D1 conducts when the voltage across the IPT (Fig. 11) 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. 12. The voltage across the interphase transformer has a frequency equal to 18 times that of the supply which results in a significant reduction in volume and cost of magnetics.

The 72-pulse converter output voltage (Fig. 13) is almost smooth and free of ripples and its average value is 607.4 volts which is approximately equal to the DC link voltage of a six-pulse rectifier (607.6 volts). This makes the 72-pulse converter suitable for retrofit applications.

Input current waveforms and its harmonic spectrum of the 6-pulse, 36-pulse and 72-pulse converters extracted and shown in Figs. 14-16, respectively to check their consistency with the limitations of the IEEE standard 519.

Table 1: Comparison of Simulated Power Quality Parameters of the Dtcimd Fed from Different AC–DC Converters

			AC Mains Current I_{SA} (A)		% THD of I_{SA}, at		Distortion Factor, DF		Displacement Factor, DPF		Power Factor, PF		DC Voltage (V)	
Sr. No.	Topology %	THD of V_{ac}	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	1.86	10.53	52.23	3.26	1.88	0.9995	0.9997	0.9986	0.9969	0.9981	0.9966	611.1	605.7
3	72-pulse	1.74	10.55	53.02	2.13	1.81	0.9998	0.9997	0.9996	0.9993	0.9994	0.9991	610.0	607.1

Table 2: Comparison of power quality indices of proposed 72-pulse ac-dc converter

	THD (%)							
Load (%)	IS	VS	CF of IS	DF	DPF	PF	RF (%)	Vdc (V)
20	2.13	0.78	1.414	0.9998	0.9996	0.9994	0.001	610.0
40	2.05	1.15	1.414	0.9998	0.9996	0.9994	0.004	609.3
60	1.89	1.41	1.414	0.9998	0.9995	0.9992	0.005	608.6
80	1.82	1.53	1.414	0.9997	0.9994	0.9992	0.001	607.9
100	1.81	1.74	1.414	0.9997	0.9993	0.9991	0.003	607.1

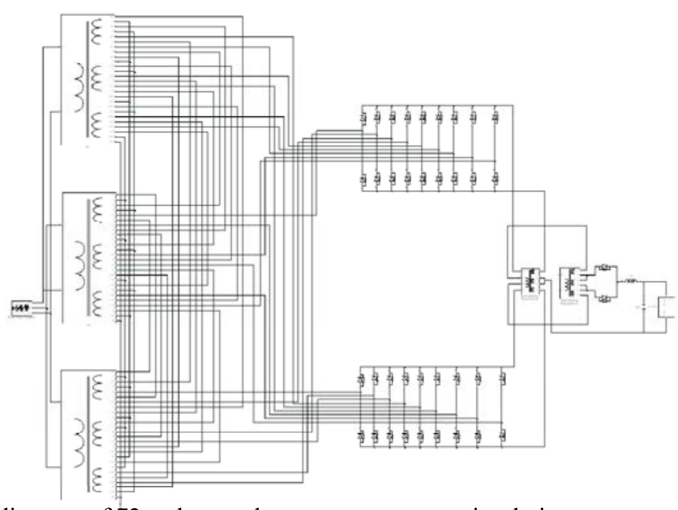

Fig. 8: MATLAB block diagram of 72-pulse ac–dc converter system simulation

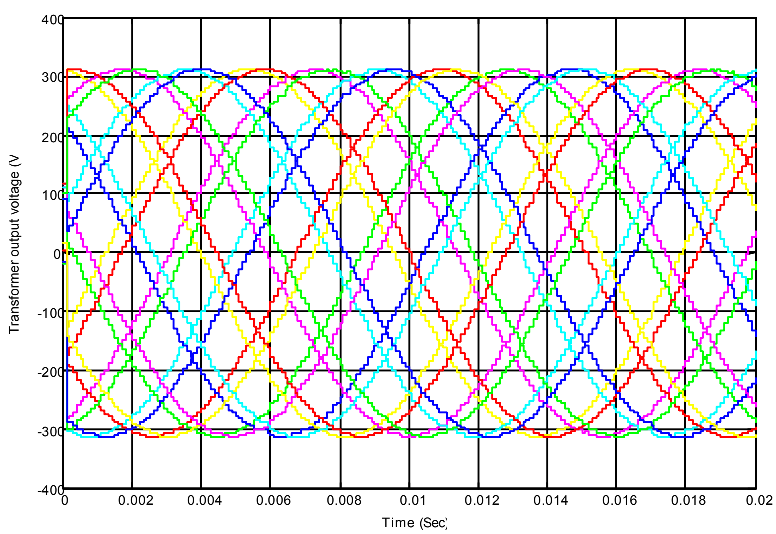

Fig. 9: Transformer output voltage

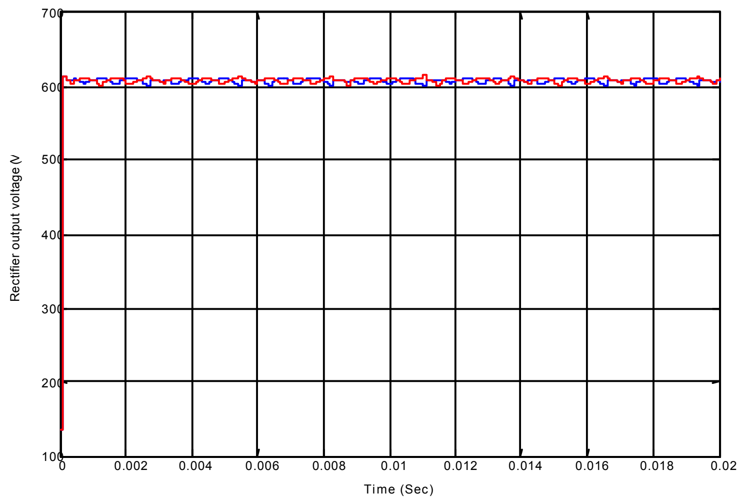

Fig. 10: Output voltage waveforms of the two parallel 10-pulse rectifiers

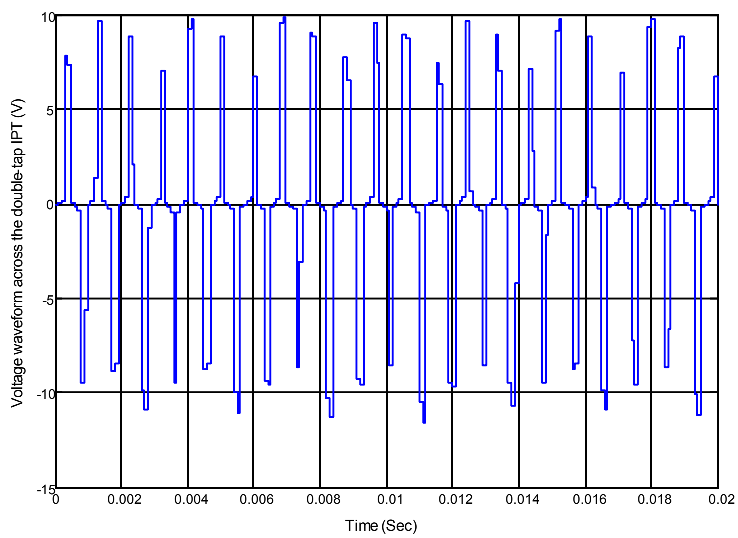

Fig. 11: Voltage waveform across the double-tap IPT

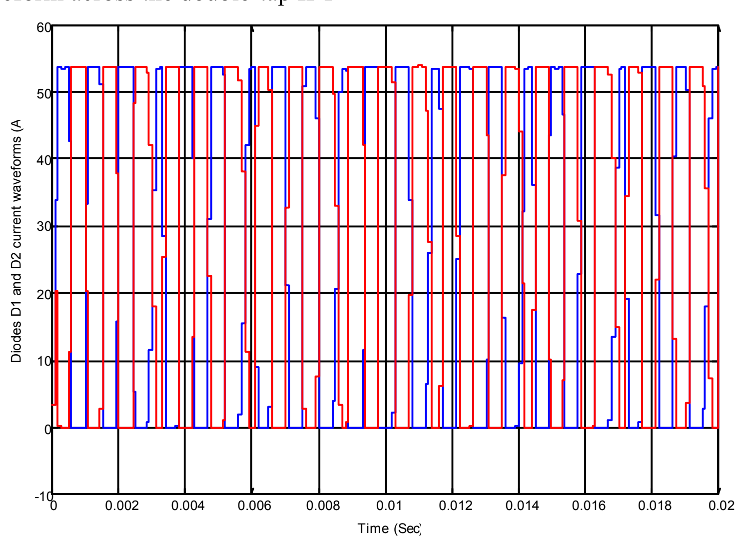

Fig. 12: Diodes D1 and D2 current waveforms

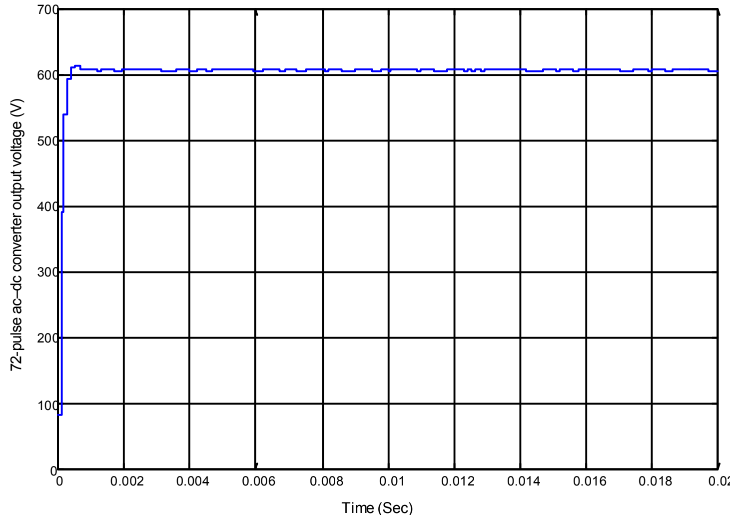

Fig. 13: 72-pulse ac–dc converter output voltage

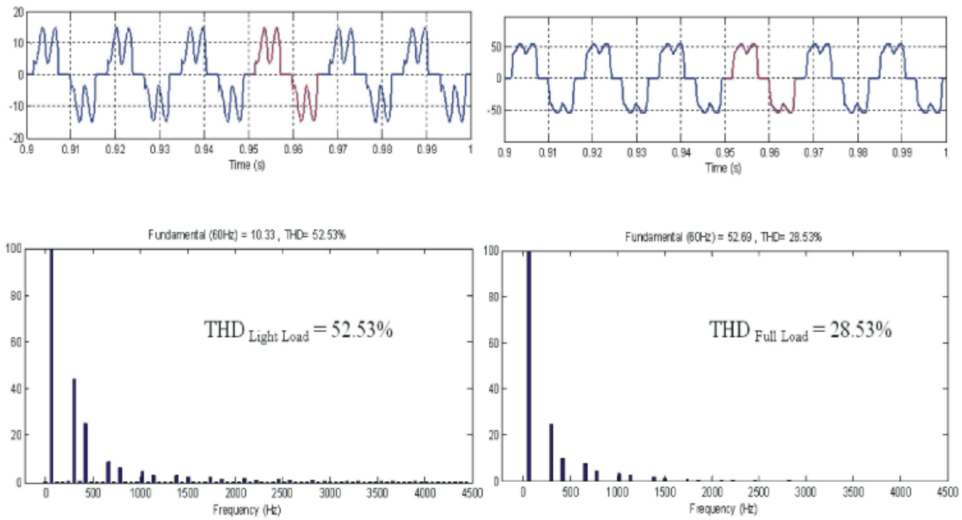

Fig. 14: Input current waveform of six-pulse ac–dc converter and its harmonic spectrum at light load and full load

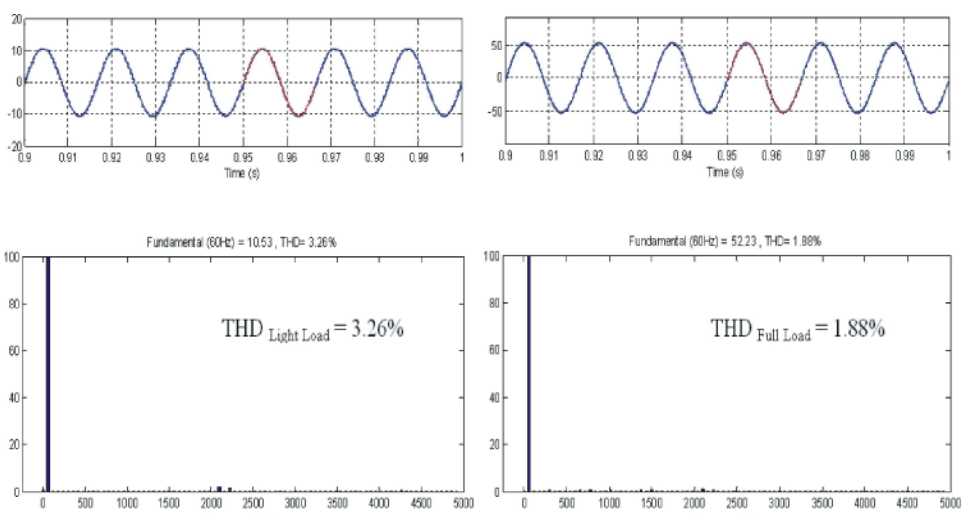

Fig. 15: Input current waveform of 36-pulse ac–dc converter and its harmonic spectrum at light load and full load

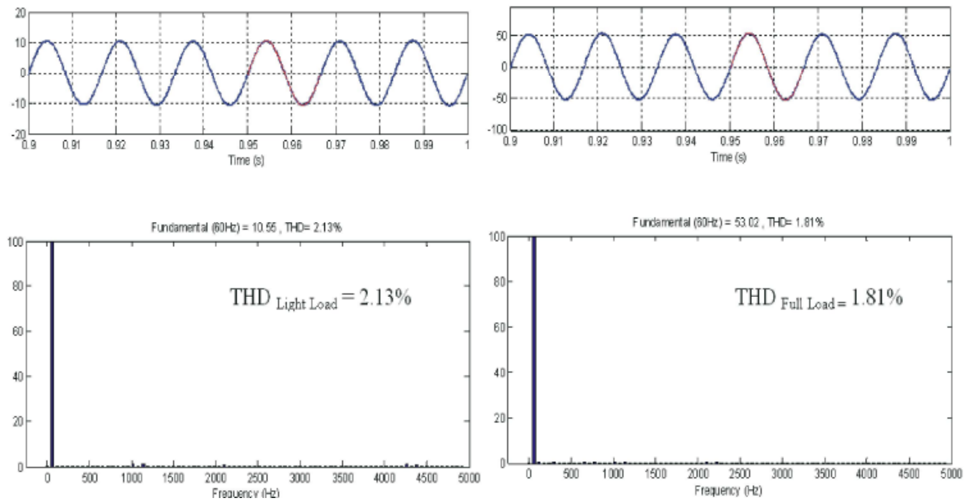

Fig. 16: Input current waveform of 72-pulse ac–dc converter and its harmonic spectrum at light load and full load

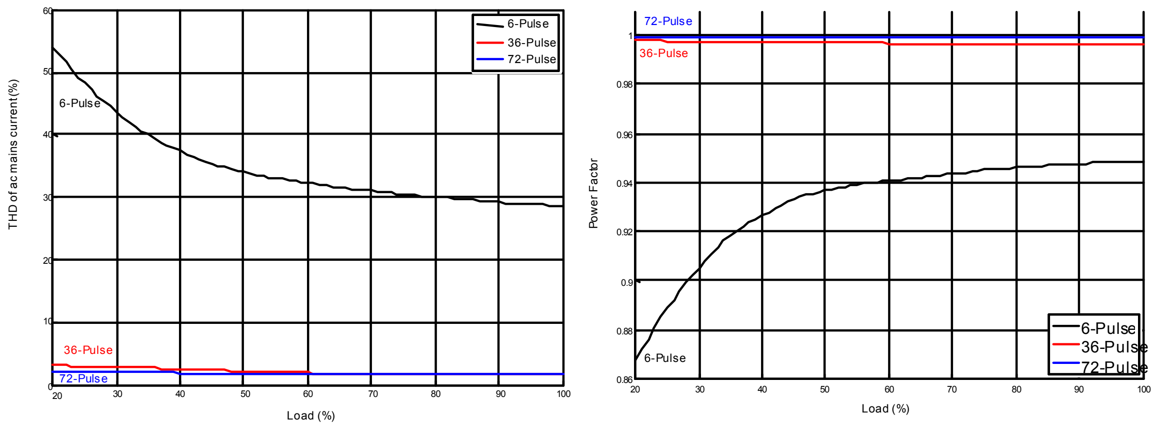

Fig. 17: Variation of THD and power factor with load on DTCIMD in 6-pulse, 36-pulse and 72-pulse ac-dc converter

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 Fig. 16, 72-pulse converter has an acceptable current THD (2.13% for light load and 1.81% for full load conditions). In this configuration, low order harmonics up to 69th are eliminated in the supply current. In general, the largely improved performance of the 72-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.

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 72-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 Fig. 17, for 6-pulse, 36-pulse and 72-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.

CONCLUSION

A novel delta/hexagon-connected transformer was designed and modeled to make a 72-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. 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. Thus, the proposed 72-pulse ac–dc converter can easily replace the existing 6-pulse converter without much alteration in the existing system layout and equipment.

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. Rs = 0.0148 Ω; Rr = 0.0092 Ω; Xls = 1.14Ω; Xlr = 1.14Ω, XLm = 3.94Ω, J = 3.1 Kg • m2.

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

DC link parameters: Ld = 2 mH; Cd = 3200 μF.

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

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