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Application of Pulse Doubling in Hexagon-Connected Transformer-Based 20-Pulse AC-DC Converter for Power Quality Improvement

Abstract. *This paper presents a pulse doubling technique in a 20-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 20-pulse rectified output voltage is accomplished via two paralleled ten-pulse ac-dc converters each of them consisting of five-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 40 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 conditions. A comparison is made between 6-pulse, 20-pulse, and proposed topology from view point of power quality indices. Simulation results show that input current total harmonic distortion (THD) is less than 5% for the proposed topology at various loads.*

Streszczenie. *W artykule zaprezentowano technikę podwojenia impulsów w 20-pulsowym przekształtniku ac-dc zastosowanym do sterowania momentem silnika. Uzyskano wygładzenie sygnału i mniejszą zawartość harmonicznych. (**Zastosowanie podwojenia liczby impulsów w 20-pulsowym przekształtniku AC-DC**)*

Keywords: AC–DC converter, hexagon-connected transformer, power quality, 40-pulse rectifier, pulse doubling, direct torque controlled induction motor drive (DTCIMD).
Słowa kluczowe: przekształtnik ac-dc, transformator podłączony hexagonalnie

Introduction

Nowadays, application of variable frequency induction motor drives (VFIMD's) is widely used in various industries such as air conditioning, blowers, fans, pumps for waste water treatment plants, textile mills, rolling mills etc [1].

Direct torque controlled strategy is the most practical technique in VFIMD's that offers better performance as compared with other control techniques. This technique is implemented in voltage source inverters which are mostly fed from six-pulse diode bridge rectifiers. The most important drawback of the six-pulse diode-bridge rectifier is its injection of harmonic currents into ac mains. The circulation of current harmonics into the source impedance results in harmonic polluted voltages at the point of common coupling (PCC) and consequently resulting in undesired supply voltage conditions and poor power quality for costumers.

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].

Due to the growth of nonlinear loads (major sources of harmonic currents) in power systems, the issue of power quality solution has been the aim of many researchers in the recent years. 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 5% for up to 24-pulse AC-DC converters. Accordingly, 30-pulse autotransformer based AC-DC converter and 36-pulse configuration have been presented in [24] and [25], respectively which Current THD is less than 5% for varying loads. The need of 30 and 36 diodes in the presented topologies of [24] and [25] respectively, is not economical.

The Polygon-Connected Autotransformer-Based 40-pulse converter [26] was designed for VCIMD's loads which Current THD is less than 5% for varying loads. The dc link voltage in this topology is higher than that of a 6-pulse diode bridge rectifier, thus making the scheme non-applicable for retrofit applications.

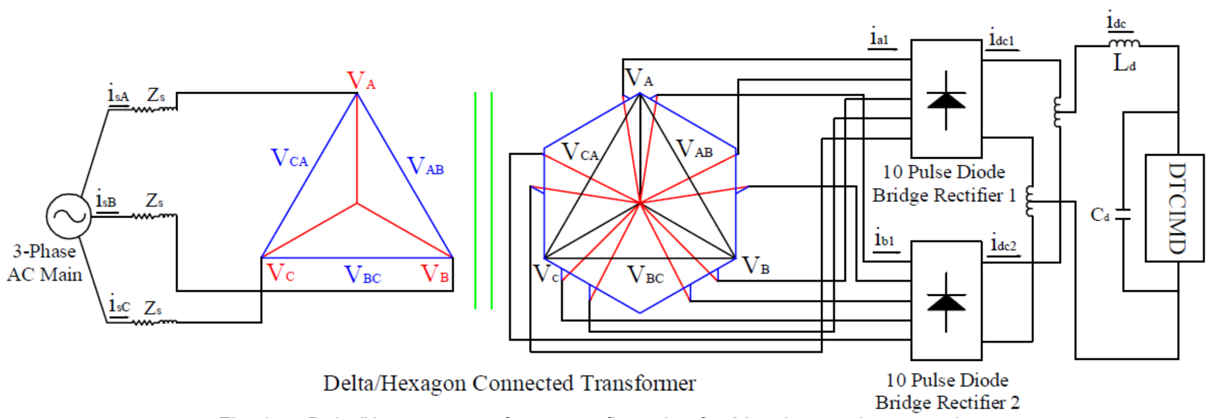

Fig. 1. Delta/Hexagon-transformer configuration for 20-pulse ac–dc conversion.

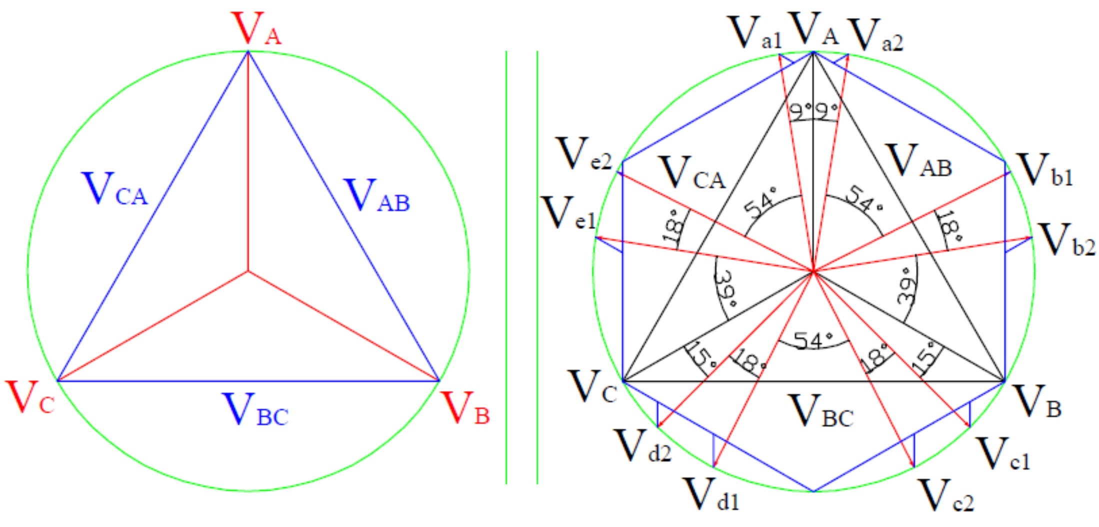

Fig. 2. Phasor representation of transformer having Hexagon connected secondary winding.

In this paper, a 40-pulse ac-dc converter is extracted from a 20-pulse ac-dc converter [34] through adding a pulse doubling circuit in the DC link. It has been observed that the number of diodes used here is 22 only, which is less than that of 24-, 30-, and 36-pulse ac–dc converters. The proposed design method will be suitable even when the transformer output voltages vary while operating in 20-pulse mode. In the proposed structure, two five-leg diode-bridge rectifiers are paralleled via a Zero Sequence Blocking Transformer (ZSBT) and fed from a transformer. Hence, a 20-pulse output voltage is obtained. In order to double the number of pulses up to 40, a tapped InterPhase 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 [29].

In other words, the removal of harmonics in 20-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 structure of 40-pulse ac-dc converter are described in this paper. 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 20-pulse ac-dc converter consisting of a hexagon transformer, two ten-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 40-pulse ac-dc converter.

Simulation results of six-pulse, 20-pulse and proposed 40-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 40-pulse AC-DC converter

As mentioned previously, the pulse-doubling technique requires a zero-sequence-blocking transformer (ZSBT) and a diode-tapped interphase reactor to multiple the number of a pulses up to 40.

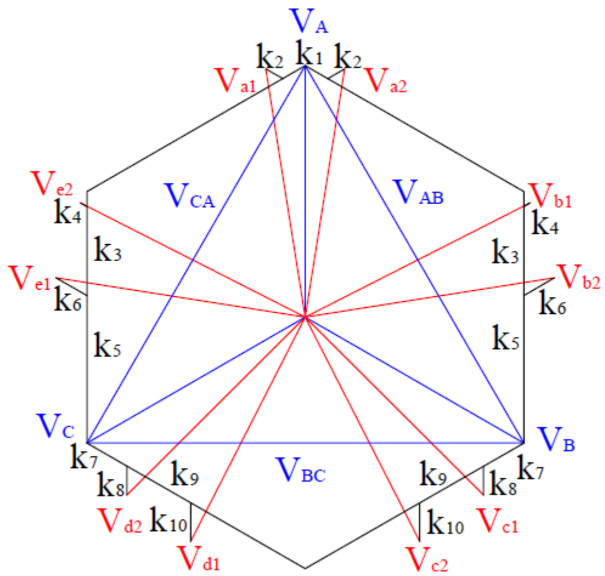

Fig. 3. Winding arrangement of hexagon transformer for produces two sets of five-phase voltages.

It is known that a 12-pulse rectified voltage can be made with two paralleled six-pulse three-phase (three-leg) diode-bridge rectifiers. The phase shift between two supplying voltages should be 30 degrees. Similarly, in order to implement a 20-pulse ac-dc converter through paralleling two bridge rectifiers, i.e. two 10-pulse rectifiers, two sets of five-phase voltages with a phase difference of 72 degrees between the voltages of each group and 18 degrees between the same voltages of the two groups are required. Accordingly, each bridge rectifier consists of five common-anode and five common-cathode diodes (two five-leg rectifiers). Phasor diagram of delta/hexagon transformer is shown in Fig. 2. The hexagon transformer winding arrangement for produce the five phase voltages is shown in Fig. 3 and its connection along with phasor diagram. An overall schematic of the proposed 40-pulse ac-dc converter is shown in Fig. 4.

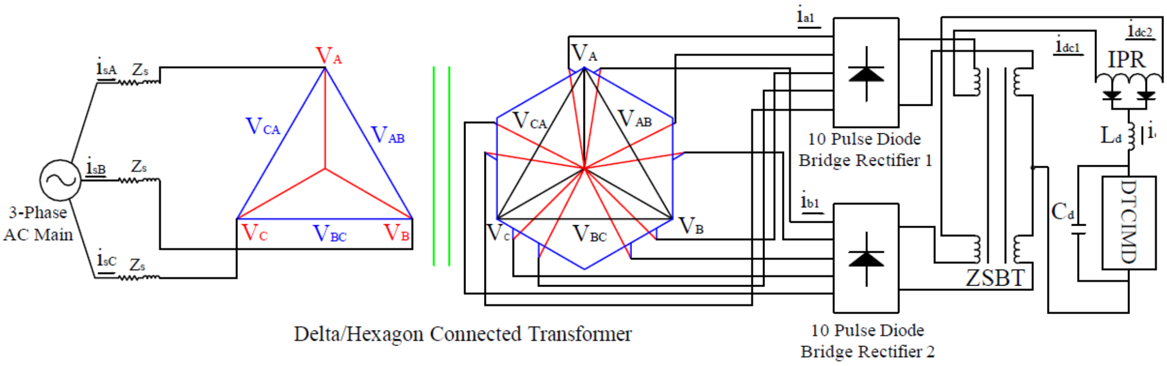

Fig. 4. Delta/Hexagon transformer configuration for 40-pulse ac–dc conversion.

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, five-phase voltages are:

(2) $$V_{a1} = V_S\angle 9^\circ,\ V_{b1} = V_S\angle -63^\circ,\ V_{c1} = V_S\angle -135^\circ,$$
$$V_{d1} = V_S\angle 153^\circ,\ V_{e1} = V_S\angle 81^\circ$$

(3) $$V_{a2} = V_S\angle -9^\circ,\ V_{b2} = V_S\angle -81^\circ,\ V_{c2} = V_S\angle -153^\circ,$$
$$V_{d2} = V_S\angle 135^\circ,\ V_{e2} = V_S\angle 63^\circ$$

Input voltages for converter I are:

(4) $$\begin{aligned} V_{a1} &= V_A + K_1 V_C - K_2 V_B \\ V_{b1} &= V_B + K_3 V_A - K_4 V_C \\ V_{c1} &= V_B + K_7 V_C - K_8 V_A \\ V_{d1} &= V_C + K_9 V_B - K_{10} V_A \\ V_{e1} &= V_C + K_5 V_A - K_6 V_B \end{aligned}$$

Input voltages for converter II are:

(5) $$\begin{aligned} V_{a2} &= V_A + K_1 V_B - K_2 V_C \\ V_{b2} &= V_B + K_5 V_A - K_6 V_C \\ V_{c2} &= V_B + K_9 V_C - K_{10} V_A \\ V_{d2} &= V_C + K_7 V_B - K_8 V_A \\ V_{e2} &= V_C + K_3 V_A - K_4 V_B \end{aligned}$$

(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_{10} are calculated using (2)-(6) to obtain the required windings turn numbers to have the desired phase shift for the two voltage sets [34]:

(7) $$\begin{aligned} &K_1 = 0.10263,\ K_2 = 0.0779,\ K_3 = 0.93955, \\ &K_4 = 0.02886,\ K_5 = 0.58618,\ K_6 = 0.14050, \\ &K_7 = 0.18348,\ K_8 = 0.11536,\ K_9 = 0.47576, \\ &K_{10} = 0.15312. \end{aligned}$$

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 40-pulse converter, the rectified output voltage is 15% 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.

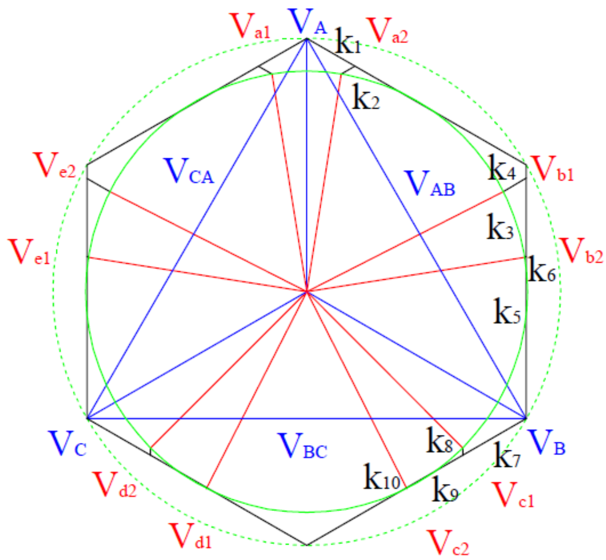

Fig. 5. Phasor diagram of voltages in the proposed transformer connection alongwith modifications for retrofit arrangement.

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 front section, the following equations can be derived as:

(8) $$|V_S| = 0.87\,|V_A|$$

Input voltages for converter I are:

(9) $$\begin{aligned} V_{a1} &= V_A + K_1 V_C + K_2 V_B \\ V_{b1} &= V_B + K_3 V_A + K_4 V_C \\ V_{c1} &= V_B + K_7 V_C + K_8 V_A \\ V_{d1} &= V_C + K_9 V_B - K_{10} V_A \\ V_{e1} &= V_C + K_5 V_A + K_6 V_B \end{aligned}$$

Input voltages for converter II are:

(10) $$\begin{aligned} V_{a2} &= V_A + K_1 V_B + K_2 V_C \\ V_{b2} &= V_B + K_5 V_A + K_6 V_C \\ V_{c2} &= V_B + K_9 V_C - K_{10} V_A \\ V_{d2} &= V_C + K_7 V_B + K_8 V_A \\ V_{e2} &= V_C + K_3 V_A + K_4 V_B \end{aligned}$$

Accordingly, the values of constants K_1-K_{10} are changed for retrofit applications as [34]:

(11) $$\begin{aligned} &K_1 = 0.21938,\ K_2 = 0.0622,\ K_3 = 0.94741, \\ &K_4 = 0.10488,\ K_5 = 0.63994,\ K_6 = 0.0077, \\ &K_7 = 0.28963,\ K_8 = 0.02963,\ K_9 = 0.54391, \\ &K_{10} = 0.0032. \end{aligned}$$

The values of K_1-K_{10} 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]:

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

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

Interphase Transformer

The theory of pulse multiplication has been presented in [29] where a tapped interphase 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 [27]-[32] 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 [33]. Likewise, we used a tapped interphase rector (IPR) to extract a 40-pulse current from two paralleled 10-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 18 degrees. As two 10-pulse rectifiers are paralleled, the voltage across the interphase transformer, V_m, has a frequency 10 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 V_m 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:

$$\begin{aligned} i_{dc1} &= (0.5 + K_t) i_{dc} \\ i_{dc2} &= (0.5 - K_t) i_{dc} \end{aligned} \tag{15}$$

where: $N_O=N_A+N_B$ and $K_t=(N_B-0.5N_O)/N_O$.

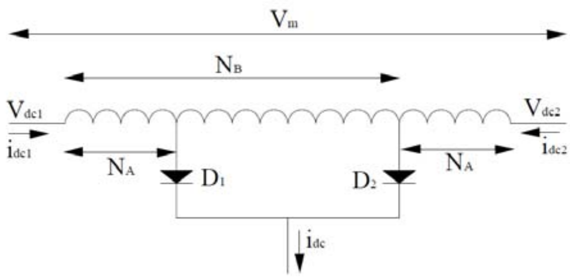

Fig. 6. Tapped Interphase Transformer circuit.

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 [29], it is proved that K_t should be equal to 0.2457 to eliminate the harmonic currents up to the 21st order which can be applied in this application too.

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 40-pulse converter, the voltage frequency of ZSBT is five times that of the supply system and it shows high impedance zero sequence (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 40-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 (C) as the dc link are connected to IGBT-based Voltage Source Inverter (VSI). VSI drives a squirrel cage induction motor employing direct torque controlled 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. 8-25. Power quality parameters are also listed in Table I for 6-pulse, 20-pulse, and 40-pulse ac-dc converters.

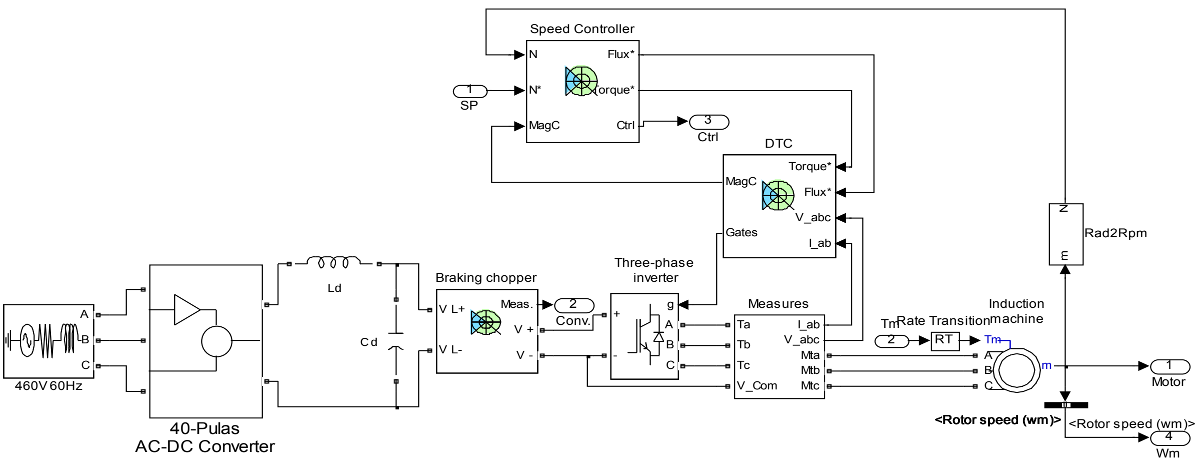

Fig. 7. Matlab model of 40-pulse ac–dc converter fed DTCIMD.

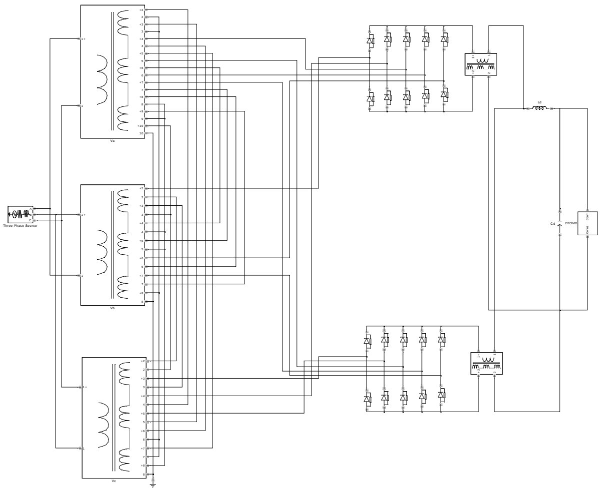

Fig. 8. Matlab block diagram of 20-pulse ac–dc converter system simulation.

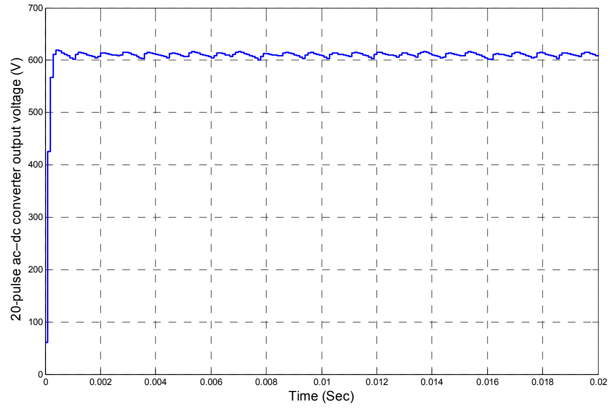

Fig. 9. 20-pulse ac–dc converter output voltage.

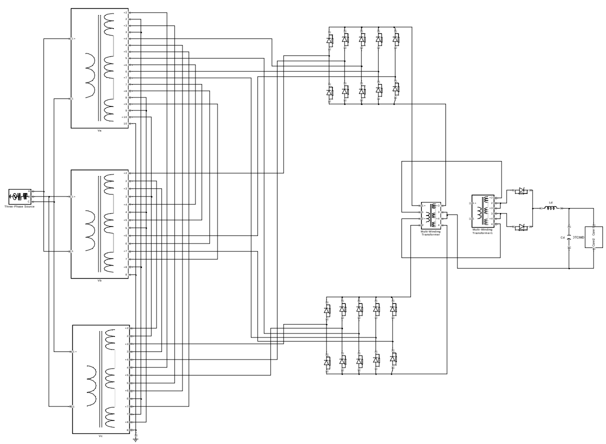

Fig. 10. Matlab block diagram of 40-pulse ac–dc converter system simulation.

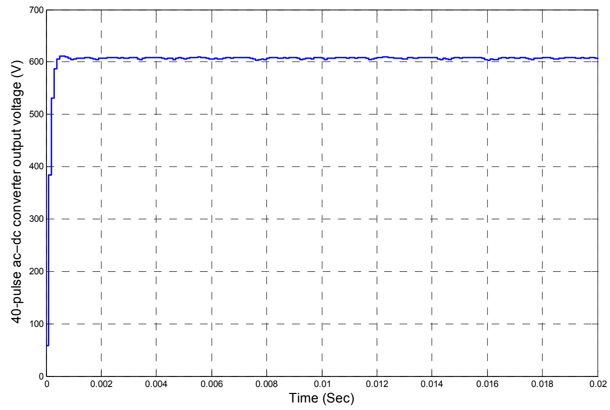

Fig. 11. 40-pulse ac–dc converter output voltage.

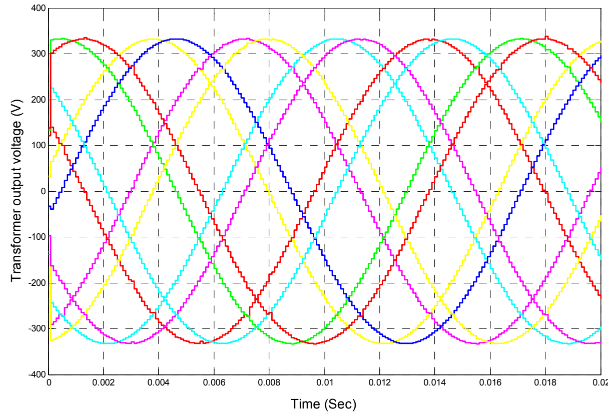

Fig. 12. Ten-pulse transformer output voltage.

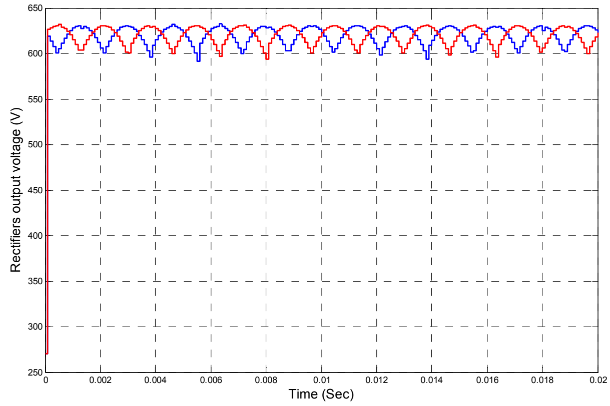

Fig. 13. Output voltage of two 10-pulse rectifiers.

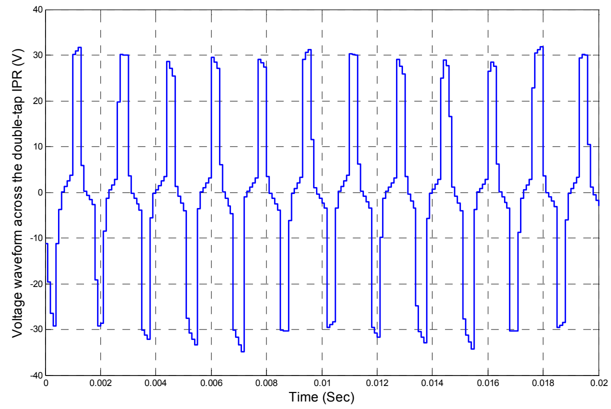

Fig. 14. Voltage waveform across the double-tap IPR.

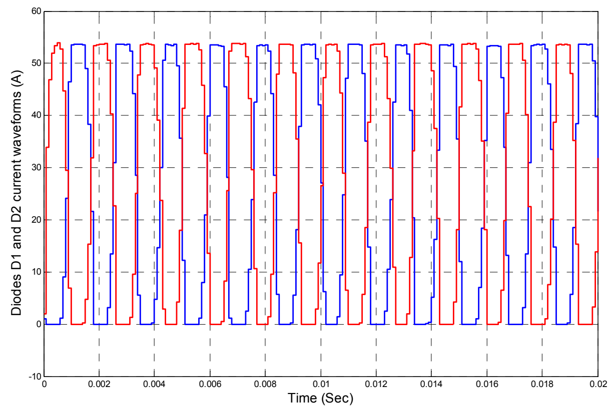

Fig. 15. Diodes D1 and D2 current waveforms.

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	5.63	10.25	52.56	52.53	28.53	0.884	0.959	0.985	0.988	0.872	0.948
2	20-pulse	3.40	10.48	52.35	7.20	5.18	0.997	0.998	0.998	0.996	0.995	0.994
3	40-pulse	2.61	10.32	52.19	4.33	3.09	0.999	0.999	0.999	0.998	0.998	0.997

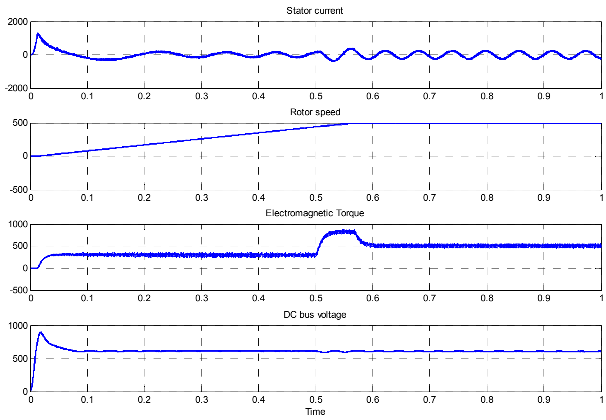

Fig. 16. Waveforms depicting dynamic response of 40-pulse diode rectifier fed DTCIMD with load perturbation (source current i_{sA}, speed ω_r , developed electromagnetic torque T_e , and dc-link voltage V_{dc}).

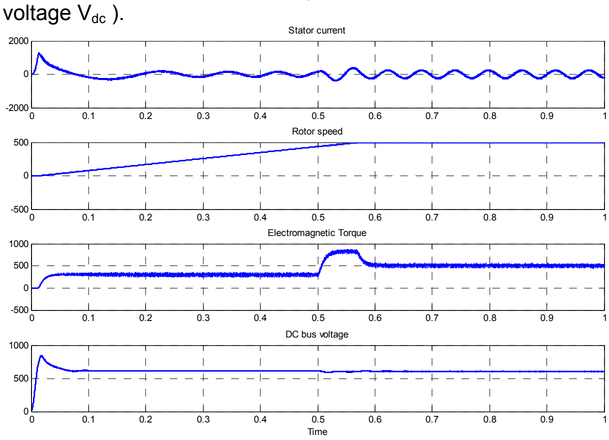

Fig. 17. Waveforms depicting dynamic response of six-pulse diode rectifier fed DTCIMD with load perturbation.

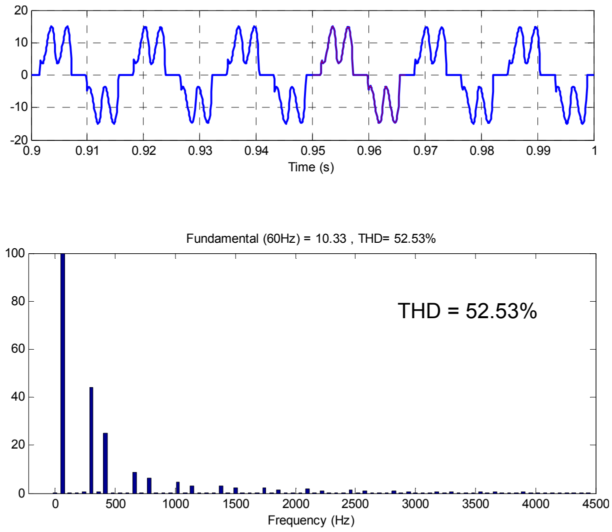

Fig. 18. Input current waveform of six-pulse ac–dc converter at light load and its harmonic spectrum.

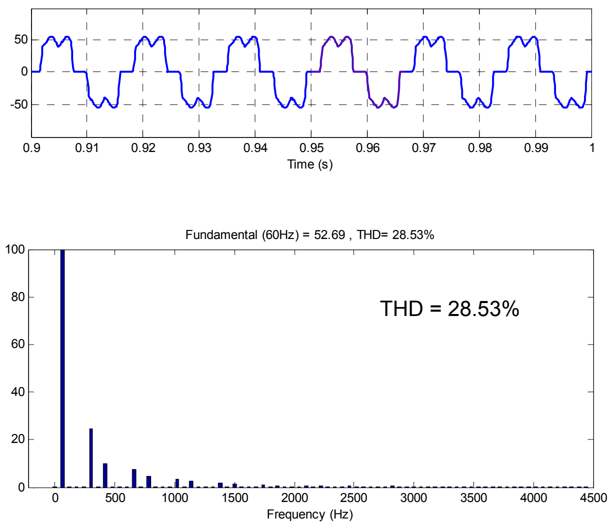

Fig. 19. Input current waveform of six-pulse ac–dc converter at full load and its harmonic spectrum.

Results and discussion

Table I lists the power quality indices obtained from the simulation results of the 6-pulse, 20-pulse, and 40-pulse converters. Matlab block diagram of 20-pulse ac–dc converter system simulation, as shown in Fig. 8, the voltage across the interphase transformer in 20-pulse ac–dc converter has a frequency equal to 5 times that of the supply which results in a significant reduction in volume and cost of magnetics, 20-pulse ac–dc converter output voltage, as shown in Fig. 9.

Matlab block diagram of 40-pulse ac–dc converter system simulation, as shown in Fig. 10. The 40-pulse converter output voltage (shown in Fig. 11) is almost smooth and free of ripples and its average value is 607.9 volts which is approximately equal to the DC link voltage of a six-pulse rectifier (607.6 volts). This makes the 40-pulse converter suitable for retrofit applications.

Fig. 12 depicts two groups of five-phase voltage waveforms with a phase shift of 18 degrees between the same voltages of each group. Two 10-pulse rectifiers output voltages with a phase difference of 18 degrees are shown in Fig. 13. The voltage across the interphase transformer (shown in Fig. 14) has a frequency equal to 10 times that of the supply which results in a significant reduction in volume and cost of magnetics.

Table II
Comparison of power quality indices of proposed 20-pulse ac-dc converter

Load (%)	THD (%)		CF of IS	DF	DPF	TPF	RF (%)	Vdc (V)
	IS	VS						
20	4.33	0.98	1.413	0.9990	0.9992	0.9982	0.006	611.8
40	3.81	1.53	1.413	0.9992	0.9989	0.9981	0.006	610.8
60	3.43	2.02	1.413	0.9992	0.9988	0.9981	0.006	609.9
80	3.18	2.33	1.413	0.9993	0.9987	0.9980	0.005	608.9
100	3.09	2.61	1.414	0.9992	0.9985	0.9978	0.003	607.9

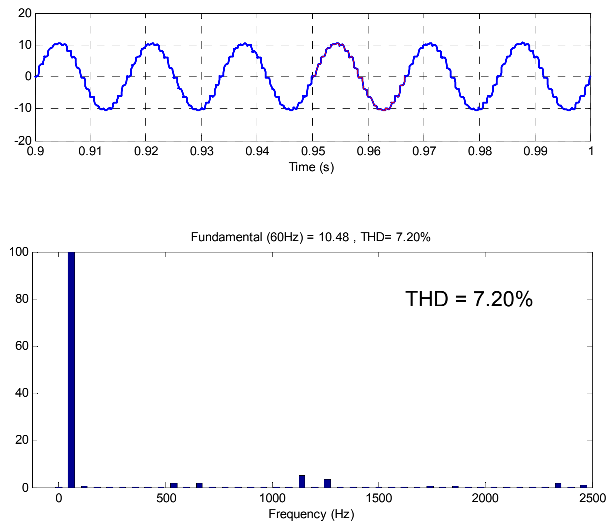

Fig. 20. Input current waveform of 20-pulse ac–dc converter at light load and its harmonic spectrum.

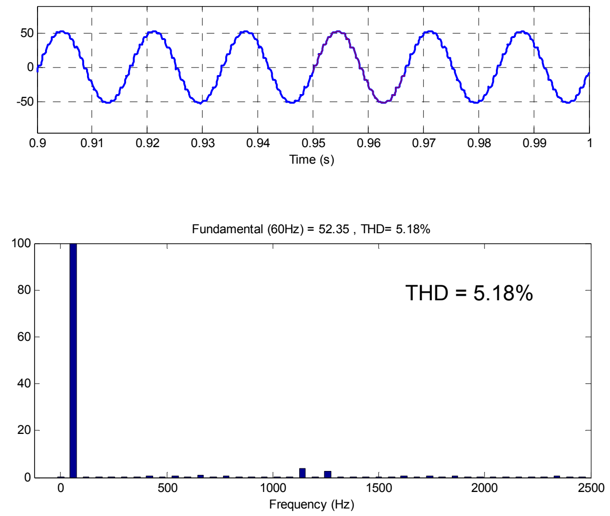

Fig. 21. Input current waveform of 20-pulse ac–dc converter at full load and its harmonic spectrum.

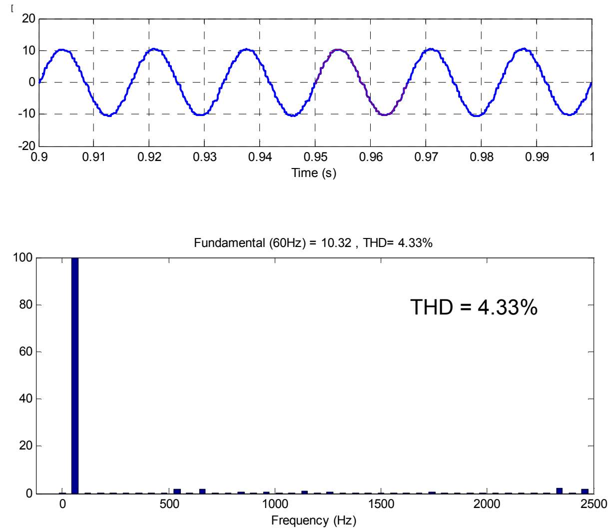

Fig. 22. Input current waveform of 40-pulse ac–dc converter at light load and its harmonic spectrum.

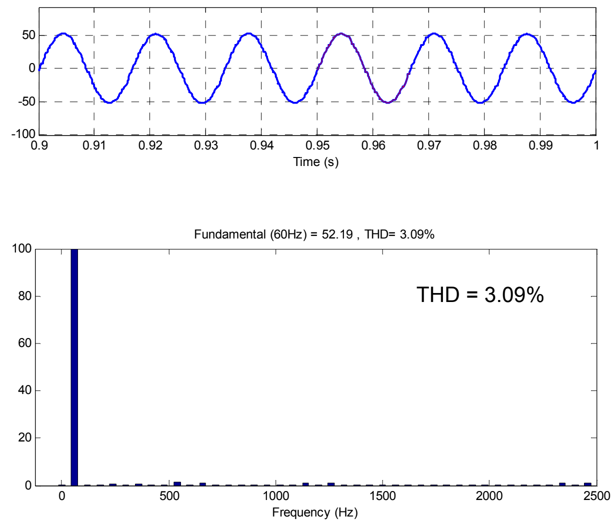

Fig. 23. Input current waveform of 40-pulse ac–dc converter at full load and its harmonic spectrum.

Diode D1 conducts when the voltage across the IPT 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 pulse doubling diodes are shown in Fig. 15.

Different output and input characteristics of the proposed 40-pulse converter feeding DTCIMD such as supply current, rotor speed, electromagnetic torque, and DC link voltage are shown in Fig. 16. These waveforms can be compared with their equivalent parameters of a six-pulse fed DTCIMD that are shown in Fig. 17. The dynamic characteristics of the two converters can be used to compare their dynamic response through conditions such as starting or load variations.

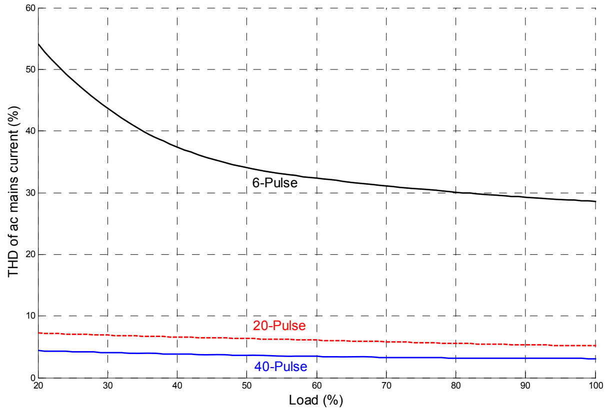

Fig. 24. Variation of THD with load on DTCIMD in 6-pulse, 20-pulse and 40-pulse ac-dc converter.

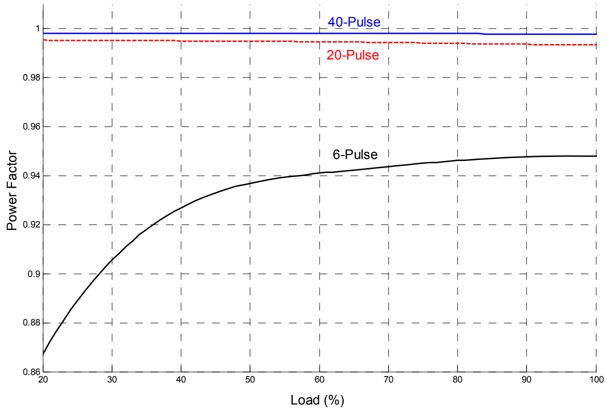

Fig. 25. Variation of power factor with load on DTCIMD in 6-pulse, 20-pulse and 40-pulse ac-dc converter

Input current waveforms and its harmonic spectrum of the 6-pulse, 20-pulse, and 40-pulse converters extracted and shown in Figs. 18-23, respectively to check their consistency with the limitations of the IEEE standard 519. These harmonic spectra are obtained when induction motor operates under light load (20% of full load) and full load conditions. 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 Figs. 22-23, 40-pulse converter has an acceptable current THD (4.33% for light load and 3.09% for full load conditions). In this configuration, low order harmonics up to 37th are eliminated in the supply current.

In general, the largely improved performance of the 40-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.

Input current THD and power factor variations are also shown in Figs. 24 and 25 respectively, for 6-pulse, 20-pulse, and 40-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 5% for the proposed topology.

Different power quality indices of the proposed topology under different loading conditions are shown in Table II. Results show that even under load variations, the 40-pulse converter has an improved performance and the current THD is always less than 5% for all loading conditions

Conclusions

A hexagon-Connected transformer-based 40-pulse ac–dc converter has been designed and modeled with a DTCIMD load. Pulse doubling has been achieved using dc-ripple re-injection technique in the 20-pulse ac–dc converter, which needs only two additional diodes along with a suitably tapped inductor. A zero-sequence-blocking transformer was added to ensure the independent operation of paralleled rectifiers and a tapped interphase 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. The design technique of the proposed converter has shown the flexibility to design the autotransformer suitable for retrofit applications. The effect of load variation on the DTCIMD on various power quality indices has also shown the efficacy of the proposed harmonic mitigator in improving these indices. The performance of the proposed harmonic mitigator has demonstrated the capability of this converter resulting in the improvement of power-quality indices at the ac mains in terms of the THD of the supply current, THD of supply voltage, power factor, and crest factor. On the dc-link side too, it provides a remarkable improvement in ripple factor of the dc-link voltage. 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 5% for varying loads. It was also observed that the input power factor is close to unity resulting in reduced input current for DTCIMD load. It has been observed that the number of diodes used here is 22 only, which is less than that of 24-, 30-, and 36-pulse ac–dc converters. Thus, the proposed 40-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 = 1.14 Ω, XLm = 3.94 Ω, 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%).

REFERENCES

[1] B. K. Bose, Modern Power Electronics and AC Drives. Singapore: Pearson Education, 1998.

[2] IEEE Standard 519-1992, IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems. NewYork: IEEE Inc., 1992.

[3] IEC Standard 61000-3-2:2004, Limits for harmonic current emissions, International Electromechanical Commission. Geneva, 2004.

[4] D. A. Paice, Power Electronic Converter Harmonics: Multipulse Methods for Clean Power. New York: IEEE Press, 1996.

[5] R. Hammond, L. Johnson, A. Shimp, and D. Harder, “Magnetic solutions to line current harmonic reduction,” in Proc. Conf. Power Con.-1994, pp. 354–364.

[6] L. J. Johnson and R. E. Hammond, “Main and auxiliary transformer rectifier system for minimizing line harmonics,” U.S. Patent 5 063 487, Nov. 1991.

[7] B. Singh, S. Gairola, A. Chandra, and K. Haddad, “Multipulse AC–DC Converters for Improving Power Quality : A Review” IEEE Transactions on Power Electronics , vol. 23, no. 1, January 2008.

[8] B. Singh, G. Bhuvaneswari, and V. Garg, “Harmonic mitigation using12-pulse ac–dc converter in vector-controlled induction motor drives,” IEEE Trans. Power Delivery, vol. 21, no. 3, pp. 1483–1492, Jul. 2006.

[9] F. J. Chivite-Zabalza, A. J. Forsyth, and D. R. Trainer, “Analysis and practical evaluation of an 18-pulse rectifier for aerospace applications,” Proc. 2nd Int. Conf. Power Electron. Mach.Drives (PEMD), vol. 1, pp. 338–343, 2004.

[10] G. R. Kamath, D. Benson, and R. Wood, “A novel autotransformer based 18-pulse rectifier circuit,” in Proc. 2001 IEEE IECON, Conf., 2002, pp. 795–801.

[11] B. Singh, G. Bhuvaneswari, and V. Garg, “Harmonic Mitigation in AC–DC Converters for Vector Controlled Induction Motor Drives” IEEE Transactions on Energy Conversion , Vol. 22, no. 3, pp. 637 - 646 , Sept. 2007.

[12] B. Singh, G. Bhuvaneswari, and V. Garg, “A Novel Polygon Based 18-Pulse AC–DC Converter for Vector Controlled Induction Motor Drives” IEEE Transactions on Power Electronics, vol. 22, no. 2, March 2007.

[13] B. Singh, V. Garg, and G. Bhuvaneswari , “A Novel T-Connected Autotransformer-Based 18-Pulse AC–DC Converter for Harmonic Mitigation in Adjustable-Speed Induction-Motor Drives” IEEE Transactions on Industrial Electronics , vol. 54, no. 5, October 2007.

[14] B. Singh, G. Bhuvaneswari and V. Garg, “Eighteen-Pulse AC-DC Converter for Harmonic Mitigation in Vector Controlled Induction Motor Drives”, in Proc. Int. Conf. on Power Electronics and Drives systems, 28 Oct.-01 Nov. 2005, Vol. 2, pp.1514 – 1519.

[15] B. Singh, G. Bhuvaneswari and V. Garg, “Nine-Phase AC-DC Converter for Vector Controlled Induction Motor Drives”, in Proc. IEEE Annual Conf. INDICON’05, 11-13 Dec. 2005, pp. 137–142.

[16] R. Hammond, L. Johnson, A. Shimp, and D. Harder, “Magnetic solutions to line current harmonic reduction,” in Proc. Conf. Power Con.-1994, pp. 354–364.

[17] B. Singh, G. Bhuvaneswari, and V. Garg, “T-Connected Autotransformer-Based 24-Pulse AC–DC Converter for Variable Frequency Induction Motor Drives” IEEE Transactions on Energy Conversion , Vol. 21, no. 3, pp. 663- 672 , Sept. 2006.

[18] B. Singh, G. Bhuvaneswari, V. Garg, and S. Gairola, “Pulse multiplication in ac–dc converters for harmonic mitigation in vector controlled induction motor drives,” IEEE Trans. Energy Conv., vol. 21, no. 2, pp.342–352, Jun. 2006.

[19] B. Singh, V. Garg, and G. Bhuvaneswari , “Polygon-Connected Autotransformer-Based 24-Pulse AC–DC Converter for Vector-Controlled Induction-Motor Drives” IEEE Transactions on Industrial Electronics , vol. 55, no. 1, pp.197–208, January 2008.

[20] B. Singh, G. Bhuvaneswari, and V. Garg, “Power-quality improvements in vector-controlled induction motor drive employing pulse multiplication in ac–dc converters,” IEEE Trans. on Power Delivery, vol. 21, no. 3, pp. 1578–1586, Jul. 2006.

[21] J. H. Traver,C.H. Peng, M. A. Massoudi, and A. A. Dauhajre, “Multiphase low harmonic distortion transformer,” U.S. Patent 4 779 181, Oct. 1988.

[22] D.Raja, N.Muraly, V.Vijayavelan, and N. Selvaganesan “ A 24-Pulse AC-DC Converter For Improving Power Quality Using Fork Connected Transformer,” International conference on control, automation, communication and energy conservation, June. 2009.

[23] Singh, S. Gairola, A. Chandra, and K.Al-Haddad “Design and Development of T- Connected Transformer Based 24-Pulse AC-DC Rectifier,” Power Electronics Specialists Conference, (PESC), June. 2008.

[24] B. Singh, G. Bhuvaneswari, and V. Garg, “An Improved Power-Quality 30-Pulse AC–DC for Varying Loads,” IEEE Trans. on Power Delivery, vol. 22, no. 2, pp. 1179 - 1187, April.2007.

[25] B. Singh and S. Gairola, “Design and Development of a 36-Pulse AC-DC Converter for Vector Controlled Induction Motor Drive,” in Proc. IEEE Conf. Power Electron. Drives Syst. PEDS’07, Nov. 27-30, 2007, pp. 694–701.

[26] B. Singh and S. Gairola, “A 40-pulse ac–dc converter fed vector controlled induction motor drive,” IEEE Trans. Energy Conv. Volume 23, no 2, pp.403 – 411 June 2008.

[27] S. Miyairi, S. Iida, K. Nakata, and S. Masukawa, “New method for reducing harmonics involved in input and output of rectifier with interhase transformer,” IEEE Trans. Ind. Appl., vol. 22, no. 5, pp. 790–797, Oct.– Nov. 1986.

[28] M. E. Villablanca and J. A. Arrilaga, “Pulse multiplication in parallel converters by multi tap control of interphase reactor,” in Proc. Inst. Elect. Eng.—B, vol. 139, no. 1, Jan. 1992, pp. 13–20.

[29] S. Choi, B. S. Lee, and P. N. Enjeti, “New 24-pulse diode rectifier systems for utility interface of high power ac motor drives,” IEEE Trans. Ind. Appl., vol. 33, no. 2, pp. 531–541, Mar.–Apr. 1997.

[30] S. Miyairi, S. Iida, K. Nakata, and S. Masubawa, “New method for reducing harmonics involved in input and output of rectifier with interphase transformer,” IEEE Trans. Ind. Appl., vol. IA-22, no. 5, pp. 790–797, Sep./Oct. 1986.

[31] P. Qijun, M. Weiming, L. Dezhi, Z. Zhihua, and M. Jin, “A New Critical Formula and Mathematical Model of Double-Tap Interphase Reactor in a Six Phase Tap-Changer Diode Rectifier” IEEE Transactions on Industrial Electronics , vol. 54, no. 1, pp.479–485, February 2007.

[32] F. Meng, S. Yang, W. Yang, and X. Jin,“ Comments and Further Results on A New Critical Formula and Mathematical Model of Double Tap Interphase Reactor in a Six-Phase Tap-Changer Diode Rectifier” IEEE Transactions on Industrial Electronics , vol. 57, no. 3, pp.950–953, March 2010.

[33] J. Arrilaga and M. Villablance, “24-pulse HVDC conversion,” Proc. Inst. Elect. Eng., vol. 138, no. 1, pp. 57–64, Jan. 1991.

[34] R. Abdollahi, "Hexagon-Connected Transformer-Based 20-Pulse AC–DC Converter for Power Quality Improvement" Journal of Electrical Systems, 8-2 (2012): 119-131

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