TAPPED DELTA AUTOTRANSFORMER-BASED 40-PULSE AC-DC CONVERTER WITH REDUCED KILOVOLT-AMPERE (KVA) RATING FOR POWER QUALITY IMPROVEMENT

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ABSTRACT*-Design of a Tapped delta autotransformer based 20-pulse ac-dc converter with reduced kilovolt-ampere (kVA) rating is presented in this paper. The 20-pulse topology is obtained via two paralleled ten-pulse ac-dc converters each of them consisting of a five-phase (five-leg) diode bridge rectifier. For independent operation of paralleled diode-bridge rectifiers, a zero sequence blocking transformer (ZSBT) is designed and implemented. Connection of a tapped inter-phase transformer (IPT) at the output of ZSBT results in doubling the number of output voltage pulses to 40. The proposed topology is basically constructed from a 20-pulse converter. The use of pulse doubling technique with a low rating (2% of the load power) results in increased number of pulses to 40. The circuit has been designed for retrofit applications, a tapped delta-connected autotransformer platform is also included to the converter. The proposed structure has been implemented and simulated using Matlab/Simulink software under different load conditions. Simulation results confirmed the significant improvement of the power quality indices (consistent with the IEEE-519 standard requirements) at the point of common coupling. Results show that input current total harmonic distortion (THD) is less than 3% for the proposed topology at variable loads. Furthermore, near unity power factor is obtained for a wide range of DTCIMD operation.*

Index Terms—AC–DC converter, Tapped delta autotransformer, power quality, 40-pulse rectifier, Pulse doubling, direct torque controlled induction motor drive (DTCIMD).

I. 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 various applications such as air conditioning, blowers, fans, pumps for waste water treatment plants, textile mills, rolling mills etc [1]. As a practical technique, direct torque control (DTC) strategy is implemented in induction motor drives (DTCIMDs), serving various applications. These drives utilize voltage source inverters which are fed from conventional six-pulse diode bridge rectifiers. The most important drawback of these rectifiers is their poor power quality injection of harmonic currents into ac mains. The circulation of current harmonics into the source impedance yields in harmonically polluted voltages at the point of common coupling (PCC) and consequently resulting in undesired supply voltage conditions for the nearby costumers [1]. The value of current harmonic components which are injected into the grid by nonlinear loads should be controlled within the standard limits.

The most prominent standards in this field are IEEE standard 519 [2] and the International Electro-technical Commission (IEC) standard [3]. For DTCIMDs one effective solution to eliminate harmonics is the use of multipulse AC-DC converters. According to the recent investigations, these converters are based on either phase multiplication, phase shifting, pulse doubling or a combined solution [4]-[26]. Application of multi-pulse technique (up to 24-pulse) in AC-DC converters are reported in [11-12] where line current THD of more than 5% is experienced under different load conditions. Design and application of multi-pulse converters for power quality improvement is reported in [14] to provide the performance of the load commutated inverter fed synchronous motor (LCI-SM) drives. A combination of passive filter and 12-pulse converter is also proposed in this paper as an alternative hardware for LCI-SM drive applications where a reduced THD of the input line current was reported. Thus, application of converters with higher number of pulses was required [18-23]. But the topologies are high cost (cost is nearly doubled), increased complexity, and higher dc-link voltage due to boost operation. A 38-pulse converter topology [24] was adopted for keeping US navy requirement of input current THD below 3%. The pulse multiplication works on the basis of ripple re-injection technique, where the power of the circulating ripple frequency is fed back to the dc system via an Interphase Transformer (IPT) resulting in reduced line current THD [21]. Ratings of IPT are small versus output apparent power. The number of turns in each IPT taps is such that the operation of diodes produces a near sinusoidal waveform in the ac line currents. The idea of pulse doubling technique was presented in [7, 11, and 12] and [25, 26] which were utilized for design of the pulse doubling circuit in this paper.

The polygon-connected autotransformer based 40-pulse converter [25] was designed for vector control induction motor drive (VCIMD) load having a current THD between 2.23% to 3.85% from full-load to light-load (20% of full-load) respectively. 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. For mitigating the total harmonic distortion (THD) problems observed in the input currents, transformer-based 40-pulse ac–dc converters have been applied [26]. However, this topologies increase the rating of magnetic parts, which finally affects the total cost of the project. In contrast, the autotransformer-based configurations [4] reduce the ratings of magnetic parts. This is true because of the fact that in this topology, only a portion of KVA rating of the induction motor should be beard by the magnetic coupling parts. Therefore, autotransformer-based configurations could significantly reduce the size and proportionally the weight of the transformer. In this paper, design of a tapped delta autotransformer based 20-pulse AC-DC converter with reduced kilovolt-ampere (kVA) rating is proposed. In the proposed structure, two five-leg diode-bridge rectifiers are paralleled via a Zero Sequence Blocking Transformer (ZSBT) resulting in a 20-pulse output voltage. In order to double the number of pulses up to 40, a Tapped Inter-Phase Transformer (IPT) with two additional diodes are added at the rectifier outputs. The proposed converters are modeled and simulated using MATLAB to study its behavior and specifically to analyze the power quality indices at ac mains.

II. PROPOSED 20-PULSE AC–DC CONVERTER

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 the two supplying voltages should be 30 degrees. Similarly, in order to implement a 20-pulse ac-dc converter, two paralleled 10-pulse bridge rectifiers (two five-leg rectifiers) are required. In this case two sets of five-phase voltages with a phase difference of 72 degrees between the voltages of each group and 18 degrees difference between the same voltages of the two groups are needed. For this purpose, a tapped delta autotransformer is designed to produce the five phase voltages. The phasor diagram of the proposed tapped delta autotransformer having two sets of 5-phase voltages with the required angular displacement is illustrated in Fig. 1.

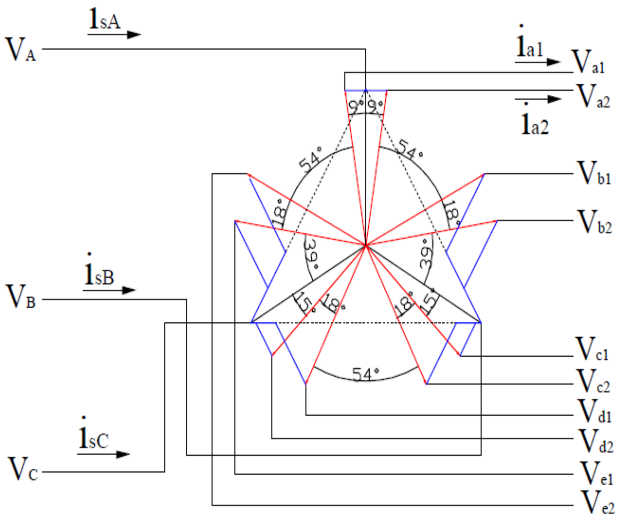

Fig. 1. Proposed autotransformer winding arrangement having tapped delta connection

A. Design of the Proposed Autotransformer for 20-Pulse AC–DC Converter

The aforementioned two voltage sets as V_{a1}, V_{b1}, V_{c1}, V_{d1}, V_{e1}, and V_{a2}, V_{b2}, V_{c2}, V_{d2}, V_{e2} are fed to rectifiers I and II, respectively. The same voltages of the two groups, i.e. Va1 and Va2, are displaced by 18 degrees.

Va1 and Va2 having a phase shift of +9 and -9 degrees from the input voltage of phase A (Va), respectively. The five-phase voltages can be made from ac mains phase and line voltages with fractions of the primary winding turns. This is illustrated in Fig. 2 with 10 constants as k_1-k_{10} representing the desired turn ratios corresponding to each winding fraction. Derivations of these constants are given by the following relationships.

$$V_A = V_s\angle 0^\circ,\ V_B = V_s\angle -120^\circ,\ V_C = V_s\angle 120^\circ. \tag{1}$$

Where Vs is the source phase voltage, V_A, V_B, and V_C are three-phase primary winding voltages. The two sets of five-phase voltages with their phase shifts are given as:

$$\begin{gathered} V_{a1} = V_S\angle 9^\circ,\ V_{b1} = V_S\angle -63^\circ,\ V_{c1} = V_S\angle -135^\circ, \\ V_{d1} = V_S\angle 153^\circ,\ V_{e1} = V_S\angle 81^\circ \end{gathered} \tag{2}$$

$$\begin{gathered} V_{a2} = V_S\angle -9^\circ,\ V_{b2} = V_S\angle -81^\circ,\ V_{c2} = V_S\angle -153^\circ, \\ V_{d2} = V_S\angle 135^\circ,\ V_{e2} = V_S\angle 63^\circ \end{gathered} \tag{3}$$

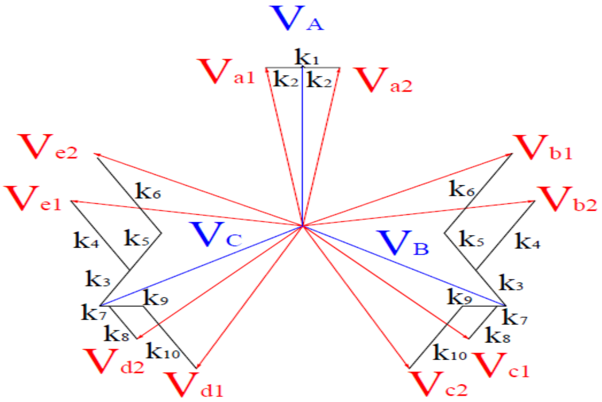

Fig. 2. Tapped delta connection of proposed autotransformer for 20-pulse converter

Using the connection arrangement of the tapped delta autotransformer shown in Fig 2, the input voltages for converters I and II are given by (4) and (5) as:

$$\begin{aligned} V_{a1} &= V_A + k_1 V_{CA} - k_2 V_{BC} \\ V_{b1} &= V_B + (k_3 + k_5) V_{AB} - k_6 V_{CA} \\ V_{c1} &= V_B - k_7 V_{BC} + k_8 V_{CA} \\ V_{d1} &= V_C + (k_7 + k_9) V_{BC} - k_{10} V_{AB} \\ V_{e1} &= V_C - k_3 V_{CA} + k_4 V_{AB} \end{aligned} \tag{4}$$

$$\begin{aligned} V_{a2} &= V_A + k_1 V_{AB} + k_2 V_{BC} \\ V_{b2} &= V_B + k_3 V_{AB} - k_4 V_{CA} \\ V_{c2} &= V_B - (k_7 + k_9) V_{BC} + k_{10} V_{CA} \\ V_{d2} &= V_C + k_7 V_{BC} - k_8 V_{AB} \\ V_{e2} &= V_C - (k_3 + k_5) V_{CA} + k_6 V_{AB} \end{aligned} \tag{5}$$

Where the line voltages are given as:

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

Constants k_1-k_{10} are calculated based on (2)-(6) to obtain the required windings turn numbers to achieve the desired phase shift for the two voltage sets as:

$$\begin{gathered} k_1 = 0.0082, k_2 = 0.08621, k_3 = 0.14855, \\ k_4 = 0.28906, k_5 = 0.15501, k_6 = 0.33243, \\ k_7 = 0.02271, K_8 = 0.13806, k_9 = 0.08484, k_{10} = 0.26066. \end{gathered} \tag{7}$$

An overall schematic of the proposed 20-pulse ac-dc converter is shown in Fig. 3

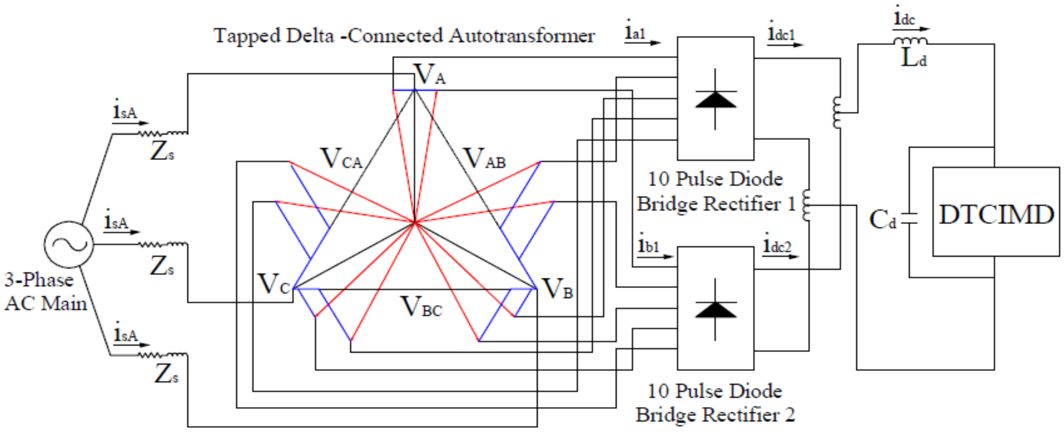

Fig. 3. Tapped delta autotransformer configuration for 20-pulse ac–dc conversion

B. *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 20-pulse converter, the rectified output voltage is 13% 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 of the windings as shown in Fig. 4. It should be noted that with this approach, the desired phase shift is still unchanged. Similar to section II part A, the following equations can be derived as:

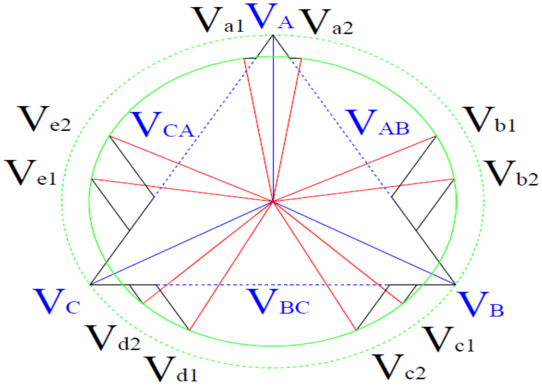

Fig. 4. Phasor diagram of voltages in the proposed autotransformer connection alongwith modifications for retrofit arrangement

$$|V_S| = 0.87|V_A| \tag{8}$$

Accordingly, the values of constants k_1-k_{10} are recalculated for retrofit applications as:

$$\begin{aligned} &k_1 = 0.0938, k_2 = 0.03167, k_3 = 0.21589, \\ &k_4 = 0.20817, k_5 = 0.13487, k_6 = 0.24588, \\ &k_7 = 0.10642, K_8 = 0.07678, k_9 = 0.07381, k_{10} = 0.18344. \end{aligned} \tag{9}$$

These values establish the essential turn numbers of the autotransformer windings to have the required output voltages and phase shifts for retrofit applications.

C. *Interphase Transformer*

Harmonic reduction in 6-pulse converters was first reported in [22] and generalized in [23]. In references [24-25] a technique called DC ripple reinjection was employed to increase pulse numbers in conventional 6-pulse converters. Application of current injection technique was also reported in [26] to reduce the input line currents harmonics of ac-dc converters. The concept of ripple reinjection has been investigated and employed by several researchers in various forms [15, 19, 27-29]. The pulse doubling scheme is used in [16] by Enjeti and widely used in research conducted by Singh et al [11-13, 21]. Pulse doubling can be achieved using a tapped inter-phase transformer (IPT) along with two additional diodes as shown in Fig. 5 [16]. Application of this technique has also been reported in several papers [30-32] mostly to increase the number of pulses and reduce the harmonic currents.

Likewise, a tapped IPT, as shown in Fig. 6, is used in this work to extract a 40-pulse current from the designed 20-pulse converter described in Section A. For the pulse multiplication process, it is necessary to ensure that the average output voltages of bridges are equal and phase shifted by 18 degrees.

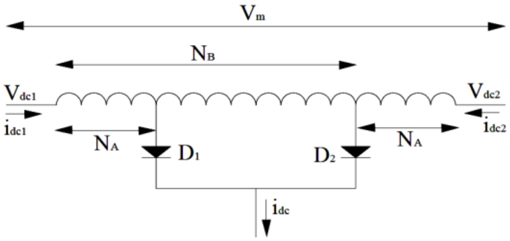

Fig. 5. Tapped Inter-phase Transformer (IPT) circuit for pulse-doubling in 20-pulse converter

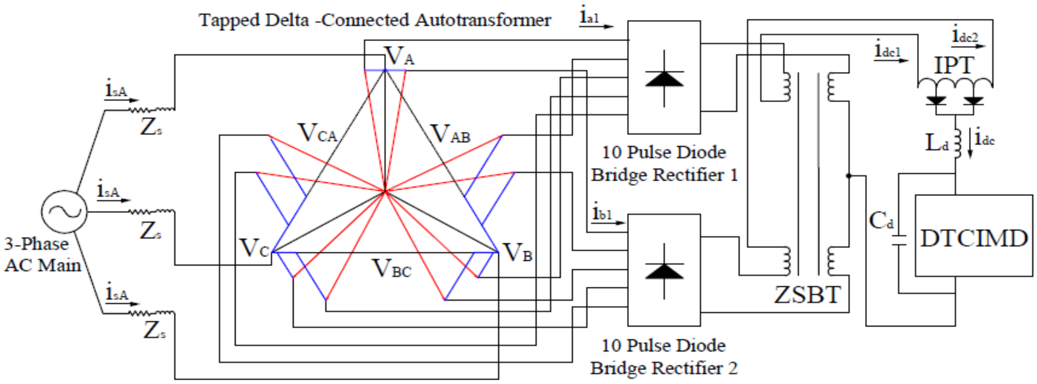

Fig. 6. Tapped delta autotransformer configuration for 40-pulse ac–dc conversion

As two 10-pulse rectifiers are paralleled, the voltage across the tapped IPT, V_m, has a frequency 10 times that of the supply. Therefore, the size, weight and volume of the tapped IPT will be reduced 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 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 can be given as:

$$i_{dc1}N_A = i_{dc2}N_B \qquad (10)$$

Where, N_A and N_B are number of turns as shown in Fig 5. Output current of each rectifier is:

$$i_{dc1} + i_{dc2} = i_{dc} \qquad (11)$$

Using (10) and (11), output current of the two rectifiers are calculated as follows:

$$\begin{aligned} i_{dc1} &= (0.5 + K_t)i_{dc} \\ i_{dc2} &= (0.5 - K_t)i_{dc} \end{aligned} \qquad (12)$$

In the above equation, $K_t=(N_B-0.5N_t)/N_t$ with $N_t=N_A+N_B$. The same relations can be written when Vm is in its negative half cycle. Therefore, according to MMF equation, the magnitude of the output currents changes which results in pulse multiplication in the supply current. In [19], it is proved that Kt should be equal to 0.2457 to eliminate the harmonic currents up to the 37th order which can be applied in this application too.

D. Zero Sequence Blocking Transformer

In parallel-rectifier configurations, the two converters cannot be directly paralleled, as the output voltages are phase-shifted, and unwanted conduction sequence of diodes is probable. Therefore, a ZSBT 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 of the supply frequency and it shows high impedance at zero sequence (and its multiples) harmonic currents and prevents them to flow. Furthermore, high ripple frequency of the ZSBT voltage makes it small and light. An overall schematic of the proposed 40-pulse ac-dc converter is illustrated in Fig. 6.

III. MATLAB-BASED SIMULATIONS

The designed configurations were simulated using Matlab/Simulink software and power system block set (PSB) toolbox. Fig. 7 shows the implemented a three-phase 460 V and 60 Hz network is utilized as the supply for the 20 and 40-pulse converters via the designed tapped delta autotransformer which is modeled by two multi-winding transformers. Multi-winding transformer block is also used for modeling of ZSBT and tapped IPT.

At the converter output (dc link), a series inductance (L) and a parallel capacitor (C) are connected to feed the IGBT-based Voltage Source Inverter (VSI). VSI drives a squirrel cage induction motor employing direct torque controlled strategy. The simulated induction motor was 50 hp (37.3 kW), 4-pole, and Y-connected. Detailed data of the simulated motor are listed in Appendix.

IV. RESULTS AND DISCUSSION

Matlab block diagram of 40-pulse ac–dc converter system simulation, as shown in Fig. 8. Simulation results are depicted in Figs. 9-19. Fig. 9 depicts two groups of five-phase voltage waveforms with a phase shift of 18 degrees between the same voltages of each group. Output voltage waveforms of the two parallel 10-pulse rectifiers with a phase difference of 18 degrees are shown in Fig. 10.

The voltage across the tapped inter-phase transformer is shown in Fig. 11 which has a frequency 10 times that of the supply frequency. Diode D_1 conducts when the voltage across the tapped IPT is positive and, conversely, D_2 is on when the voltage across it is in its negative half-cycle. 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. 12. The magneto-motive force (MMF) equivalence of the tapped IPT windings is formulated using equation (12).

The 40-pulse converter output voltage (shown in Fig. 13) is almost smooth and free of ripples with average value of 607.9 V, which is approximately equal to the DC link voltage of a six-pulse rectifier (607.6 V). This makes the 40-pulse converter suitable for retrofit applications.

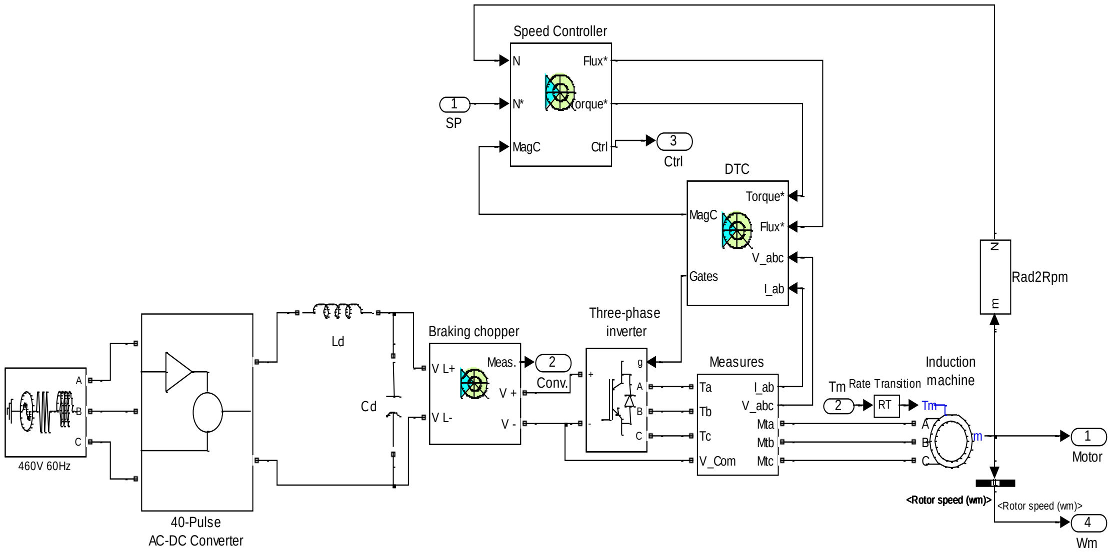

Fig. 7. Matlab model of 40-pulse ac–dc converter fed DTCIMD

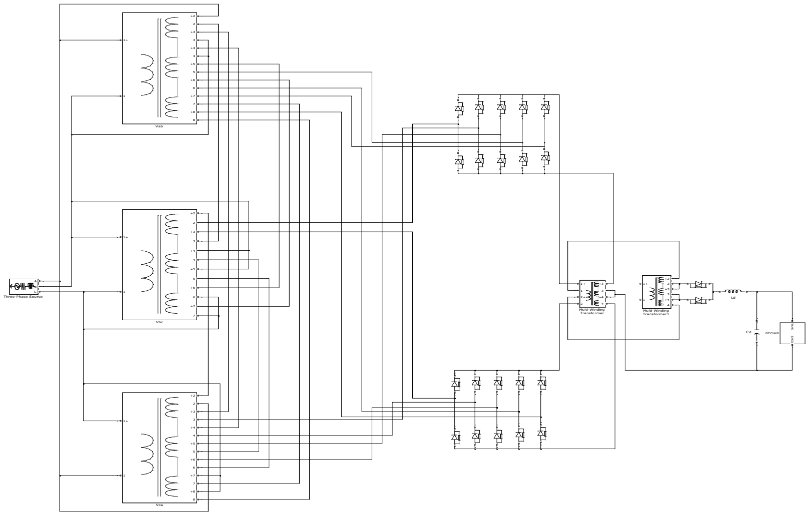

Fig. 8. Matlab block diagram of 40-pulse ac–dc converter system simulation

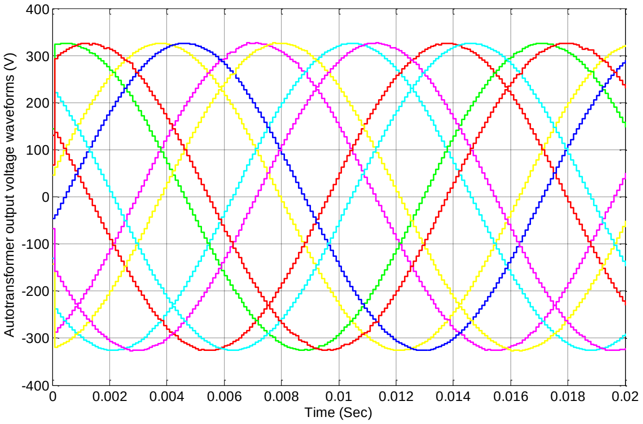

Fig. 9. Ten-phase autotransformer output voltage waveforms

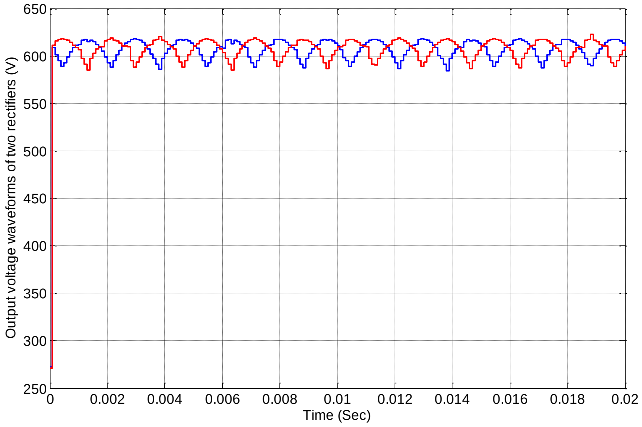

Fig. 10. Output voltage waveforms of the two parallel 10-pulse rectifiers

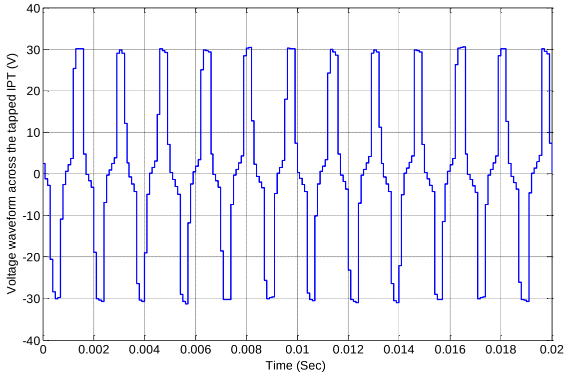

Fig. 11. Voltage waveform across the tapped IPT

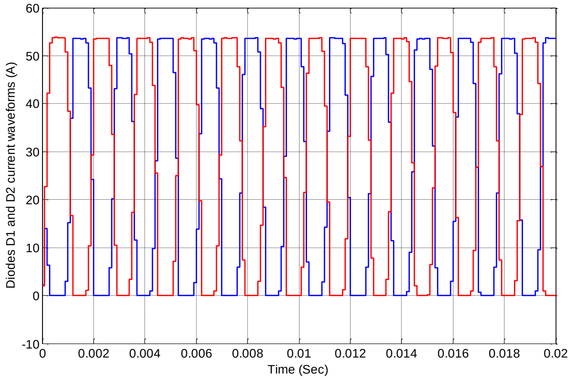

Fig. 12. Diodes D1 and D2 current waveforms

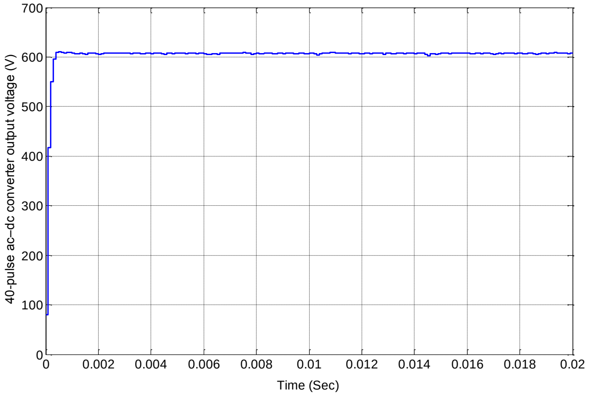

Fig. 13. 40-pulse ac–dc converter output voltage

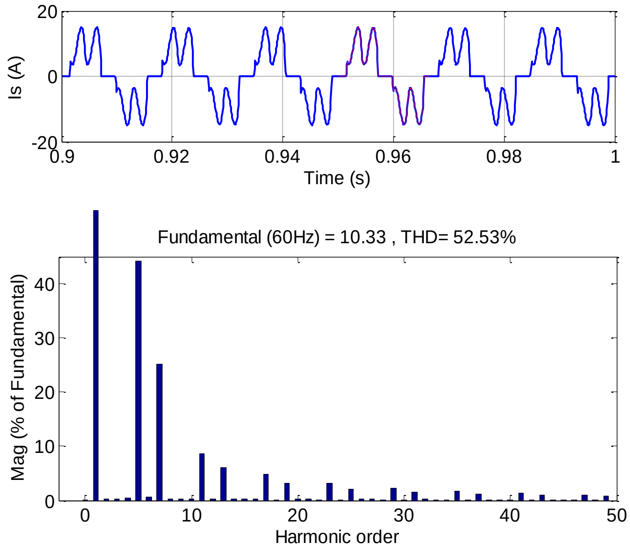

Fig. 14. Input current waveform of six-pulse ac–dc converter at light load and its harmonic spectrum

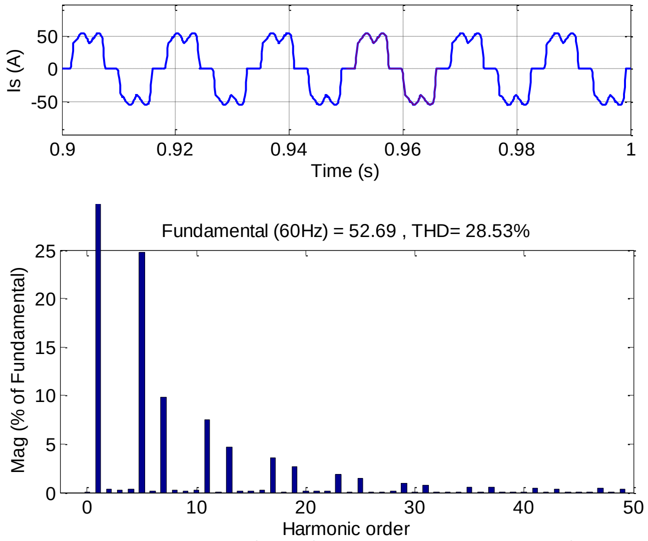

Fig. 15. Input current waveform of six-pulse ac–dc converter at full load and its harmonic spectrum

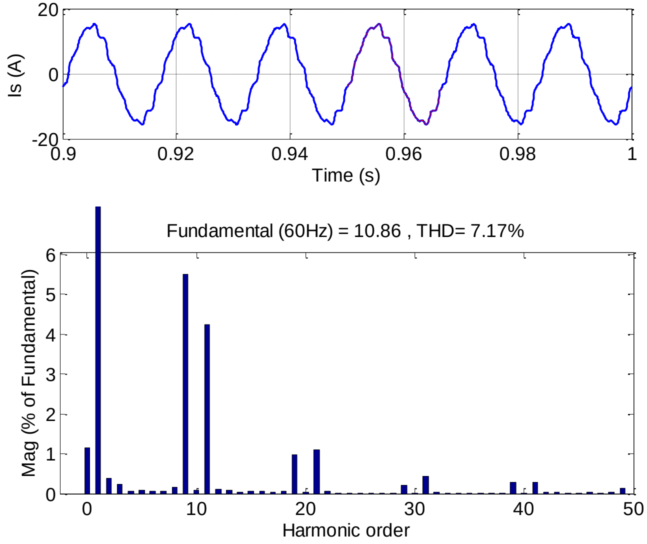

Fig. 16. Input current waveform of 20-pulse ac–dc converter at light load and its harmonic spectrum

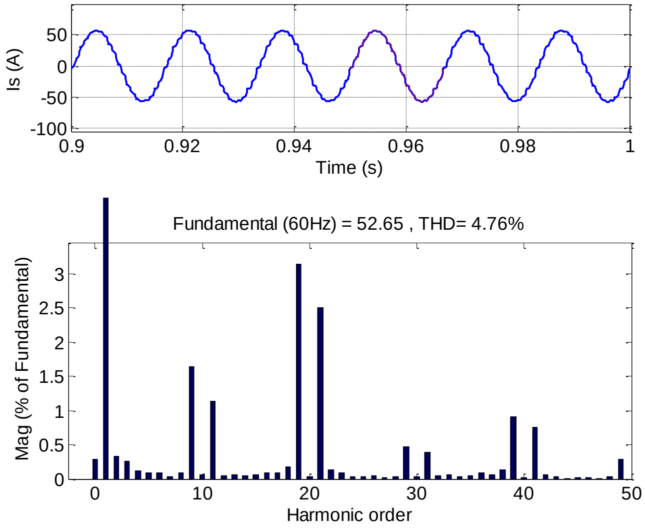

Fig. 17. Input current waveform of 20-pulse ac–dc converter at full load and its harmonic spectrum

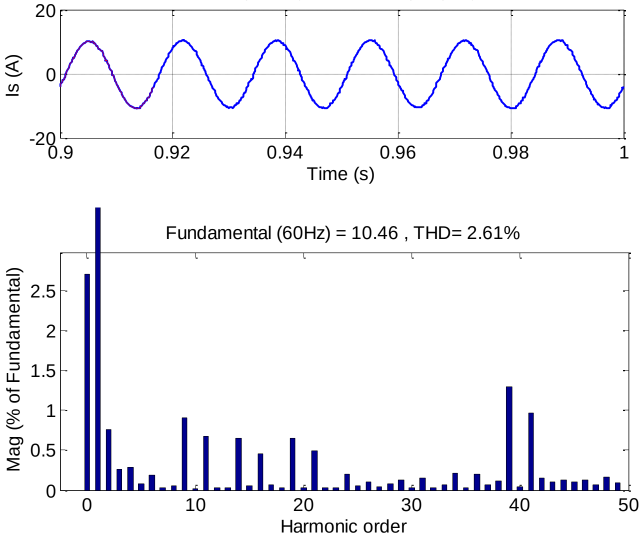

Fig. 18. Input current waveform of 40-pulse ac–dc converter at light load and its harmonic spectrum

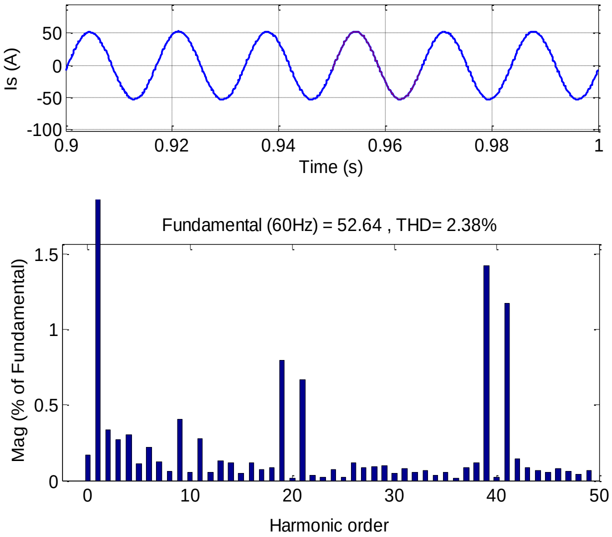

Fig. 19. Input current waveform of 40-pulse ac–dc converter at full load and its harmonic spectrum

TABLE I

COMPARISON OF POWER QUALITY PARAMETERS FOR DIFFERENT SIMULATED AC–DC CONVERTERS

Sr. No.	Topology	% THD of V_{ac}	AC Mains Current I_{SA} (A)		% THD of I_{SA}, at		Distortion Factor, DF		Displacement Factor, DPF		Power Factor, PF		DC Voltage (V)	
			Light Load	Full Load	Light Load	Full Load	Light Load	Full Load	Light Load	Full Load	Light Load	Full Load	Light Load	Full Load
1	6-pulse	*5.63*	*10.33*	*52.69*	*52.53*	*28.53*	*0.884*	*0.959*	*0.985*	*0.988*	*0.872*	*0.948*	*616.6*	*607.6*
2	20-pulse	*2.84*	*10.86*	*52.65*	*7.17*	*4.76*	*0.997*	*0.998*	*0.948*	*0.992*	*0.946*	*0.990*	*610.9*	*604.6*
3	40-pulse	*2.58*	*10.46*	*52.64*	*2.61*	*2.38*	*0.999*	*0.999*	*0.963*	*0.995*	*0.962*	*0.995*	*610.8*	*607.9*

Input current waveforms and its harmonic spectrum of the 6-pulse, 20-pulse, and 40-pulse converters extracted and shown in Figs. 14-19, 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.

The input current THD of the typical 6-pulse converter is equal to 28.53% and 52.53% for full load and light load conditions respectively, as illustrated in Figs 14 and 15. As expected, these figures are relatively large which are not within the standard margins. The presence of low order harmonics is also one of the drawbacks of these types of converters. The current THD for the proposed 20-pulse converter is reduced to 4.76% and 7.17% for full load and light load conditions respectively as shown in Figs. 16 and 17. These figures are still beyond the 5% limit set by IEEE standard. However, it can be seen that low order harmonics up to 17th are significantly eliminated in the supply current due to the proper operation of pulse multiplication.

The use of proposed 40-pulse converter has resulted in an acceptable current THD of 2.61% for light load and 2.38% for full load conditions as shown in Figs. 18 and 19. In this configuration, low order harmonics up to 37th are further eliminated in the supply current. In addition to the supply current THD, other power quality indices such as supply voltage THD, displacement power factor (DPF), distortion factor (DF), and power factor (PF) are also calculated under different loading conditions and shown in Table I. It can be seen that these indices are significantly improved as higher pulse number converters are utilized. Moreover, the mains power factor for the 40-pulse topology has reached unity from light load to full load conditions.

V. CONCLUSIONS

In this paper a tapped delta autotransformer was designed, modeled and simulated to investigate the operation of a 20-pulse ac-dc converter consisting of two paralleled 10-pulse five-phase rectifiers. Being capable for retrofit applications, the proposed design procedure was modified for this purpose. The proposed topology is basically constructed from a 20-pulse converter. The use of pulse doubling technique with a low rating (2% of the load power) results in increased number of pulses to 40. The increased number of pulses results in decreasing the size and volume of the transformers as well as improvement of the power quality indices at the pcc. Simulation results demonstrated the proper operation of the proposed configuration with good agreement within the limits set by IEEE-519. In summary, 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 summary, 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.

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