Open Access Journal

Journal of Power Technologies 99 (4) (2020) 281–288

journal homepage:papers.itc.pw.edu.pl

Technical and economical comparison of different autotransformer based 36 pulse AC-DC Converters

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Abstract

Three-phase multipulse ac–dc converters (MPC) are being developed to improve power quality to reduce harmonics in ac mains and ripples in dc output. This study, based on technical and economic factors, compares different autotransformer based 36 pulse AC-DC Converters. This paper presents a comparison of tapped delta, polygon and T connected autotransformer based 36-pulse AC-DC converters. These converters were implemented and simulations were made using Matlab/Simulink software for similar ratings under different load conditions. A set of power quality indices on input ac mains and on a dc bus for a DTCIMD fed from different 36-pulse ac-dc converters is given to compare their performance. The economic comparison of 36 pulse ac–dc converters is based on the apparent power (kVA) ratings of the different autotransformers for 36 pulse AC-DC converters. Also, a prototype is developed and the experimental measurements obtained are presented to validate the feasibility and operability of the 36-pulse AC-DC converter. The 36-pulse AC-DC converter offers a total harmonic distortion of 4% and can operate at near-unity power factor, in compliance with IEEE and IEC standards.

Keywords: AC-DC converter, power quality, 36-pulse rectifier, direct torque controlled induction motor drive (DTCIMD)

1. Introduction

As a practical technique, direct torque control (DTC) strategy is implemented in induction motor drives (DTCIMDs), serving various applications such as air conditioning, blowers, fans, pumps for waste water treatment plants, cement industry, ship propulsion, rolling mills, etc. These direct torque-controlled induction motor drives (DTCIMDs) are fed by conventional six-pulse diode bridge rectifiers, which results in the injection of current harmonics into ac mains, thereby polluting power quality at the point of common coupling (PCC). The circulation of current harmonics, while propagating through finite source impedance, result in voltage distortion at the point of common coupling, thereby affecting consumers nearby [1]. Important international standards in this field – IEEE standard 519 [2] and the International Electrotechnical Commission (IEC) standard [3] – deal with limiting voltage and current distortions. For DTCIMDs one effective solution to eliminate harmonics is the use of multipulse AC-DC converters. According to recent investigations, these topologies are based on the principle of increasing the number of pulses in ac–dc converters, such as either phase multiplication, phase shifting, pulse doubling or a combined solution [4–7]. However, when operating at light load or small source impedance, line current total harmonic distortion (THD) will be more than 5% for up to 24-pulse configurations. Recently, a Hexagon-Connected 20-pulse converter has been reported [6] to reduce harmonics and has THD variation of 5.18% to 7.20% from full-load to light-load (20% of full-load). AC-DC converters of up to 24-pulse were addressed in [8–11] as an application of multipulse technique, but the proposed schemes lead to violation of IEEE 519 requirements (5% for input current THD). A T-Connected Autotransformer-Based 24-pulse AC-DC converter is reported in [12] which has a THD variation of 2.46% to 5.20% from full-load to light-load (20% of full-load). Another double Zigzag-Connected Autotransformer-Based 24-Pulse AC–DC Converter was presented in [13], but the THD of the supply current with this topology is reported to vary from 3.95% to 5.85%, and more than 5% when operating at light load. Different 30-pulse rectifiers have been reported in the literature for power quality improvement [14, 15], and they included T [15] and fork [14]-connected autotransformer based 30-pulse AC-DC converters.

However, the THD of ac mains current with these topologies is more than 3% when operating at light load. The 36-pulse rectifier in [16] has THD variation of 2.03% to 3.74% from full-load to light-load (20% of full-load) respectively, but the dc link voltage is higher than that of a 6-pulse diode

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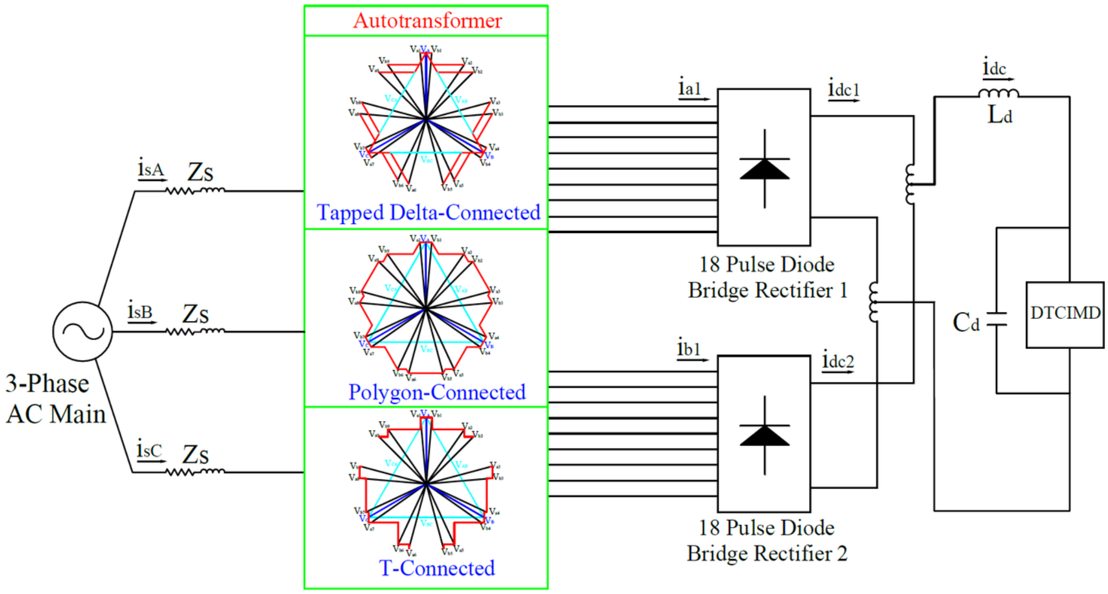

Figure 1: Autotransformer baed 36 pulse AC-DC Converters.

bridge rectifier, thus making it non-applicable for retrofit applications. Various 36-pulse transformer-based rectification schemes [17–19] have been reported and used in practice for the purpose of line-current harmonic reduction. With transformer-based multiple converters, the power quality indices show an improvement, but at the cost of large magnetics, resulting in higher cost of the drive [4]. Therefore, autotransformer-based schemes could significantly reduce the KVA rating of the converter. In this paper, we compare three 36-pulse rectifiers based on tapped delta [20], polygon [21], and T [22]-connected autotransformer (shown in Fig. 1) with kVA rating and power quality parameters such as total harmonic distortion (THD) of ac mains current and voltage, power factor (PF), displacement factor (DPF), and distortion factor (DF) at the PCC under the same output power.

2. 36-Pulse AC-DC Converter

The minimum phase shift required for proper harmonic elimination is calculated as [4]:

$$PhaseShift = \frac{360°}{NumberofConverters \cdot NumberofPulse}$$

Two sets of nine-phase voltages must be generated to achieve 36-pulse ac–dc conversion. Having paralleled two sets of 18-pulse bridge rectifiers, a 36-pulse AC-DC converter will be obtained. In other words, parallel connection of two 10 degrees phase shifted sets of 9-phase system of voltages, which are 40 degrees phase shifted with respect to each other, would give us a different 36-pulse AC-DC converter (Fig. 1). Fig. 2 shows the winding arrangement along with the phasor diagram of different 36-pulse ac–dc converters.

3. Matlab-Based Simulation

MATLAB/SIMULINK software was used to simulate different autotransformer based 36 pulse AC-DC Converters for and comparison purposes. The 36-pulse converter provides a DC link from a three-phase 460 V 60 Hz system for an AC induction motor drive. The 36 pulse rectifiers and IPT are modeled using three multi-winding transformers. The simulation results are depicted in Figs. 3-9. Power quality parameters are also listed in Table 1 for 6-pulse, and various 36-pulse ac-dc converters. The rating of the input transformer is calculated based on the simulated rms values of the voltage and current.

4. Result and Discussions

The two systems of 9-phase voltages are depicted in Fig. 3. As can be seen in this figure, the voltages have a 10 degrees phase shift. The voltage obtained at the terminal of the inter-phase transformer (IPT) is shown in Figure 4. The voltage waveform of the proposed scheme is illustrated in Fig. 5. A smooth regulated DC voltage of 608.9 V is obtained, which is comparable with the DC output voltage of a conventional 6-pulse converter.

Input current waveforms and its harmonic spectrum of the 6-pulse and different 36-pulse converters (tapped delta, polygon and T) extracted and shown in Figs. 6-9, respectively to check their consistency with the limitations of the IEEE standard 519. These harmonic spectrums are obtained when induction motor operates under light load (20% of full load) and full load conditions. Obviously, for the 6-pulse converter, fifth and seventh order harmonics are dominant. Hence, input current THD of this converter will be relatively large: 28.53% and 52.53% for full load and light load

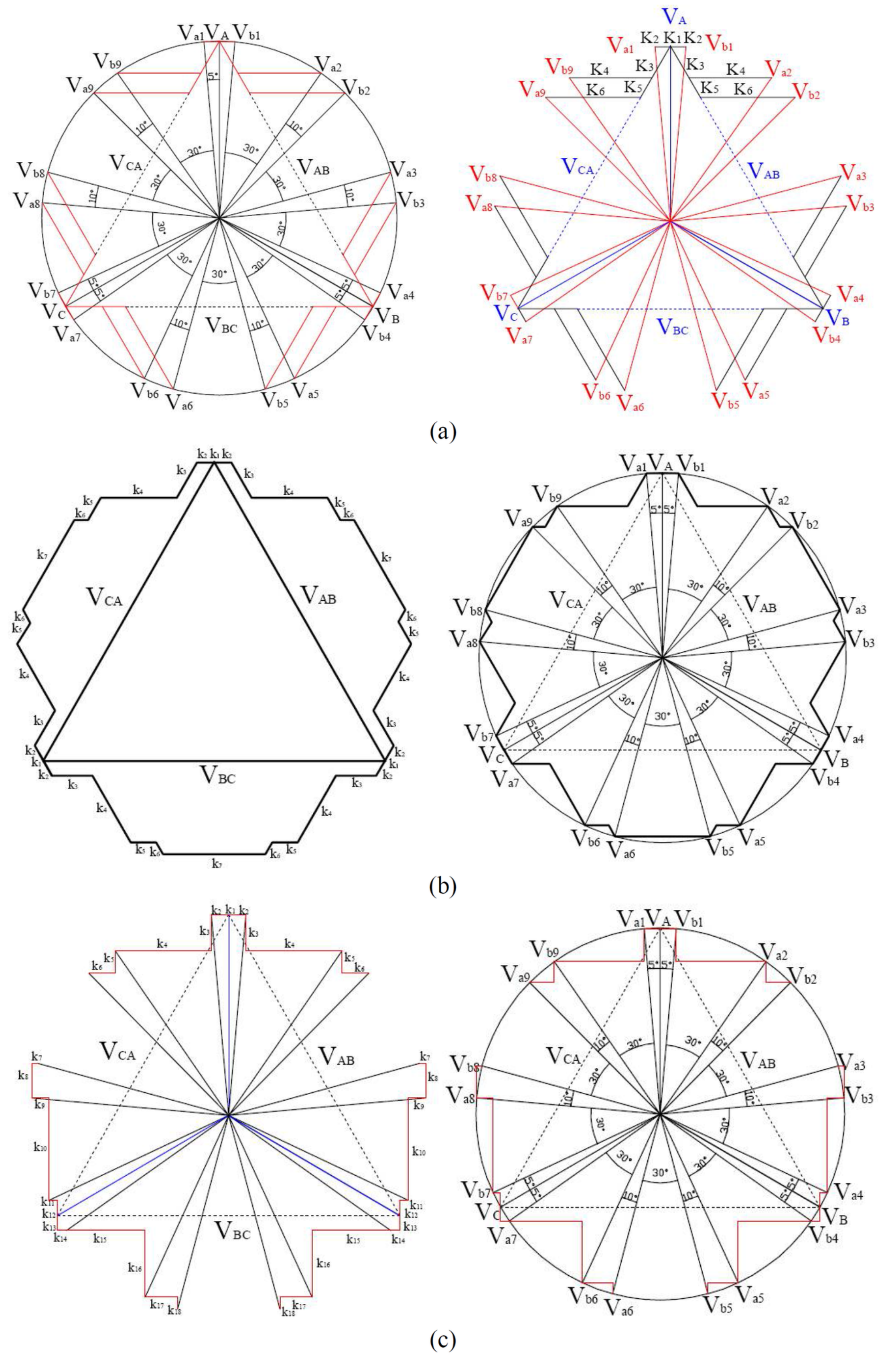

Figure 2: (a) Tapped delta, (b) Polygon, and (c) T-connection of autotransformer for 36-pulse converter and its phasor representation

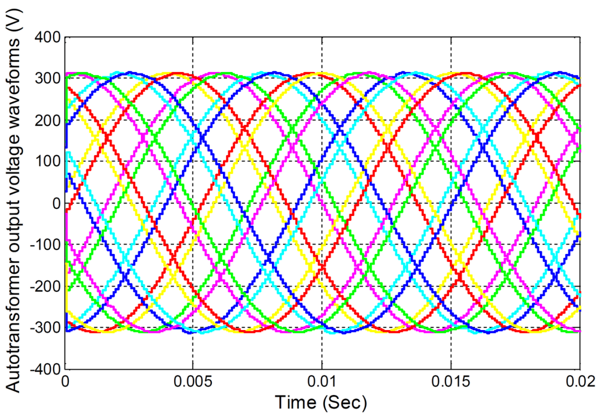

Figure 3: Output voltage waveforms for 18-phase transformer

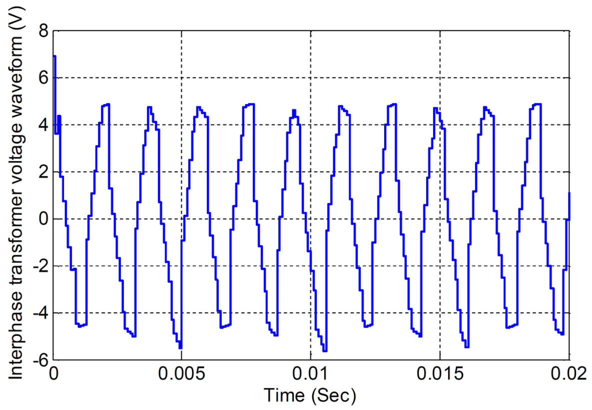

Figure 4: Voltage waveform across the interphase transformer

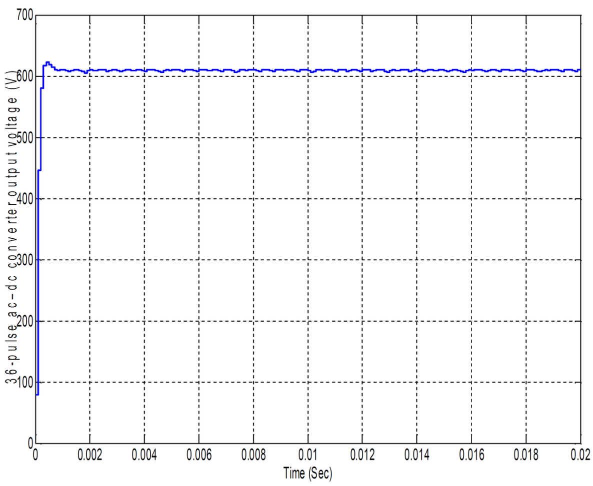

Figure 5: Output voltage waveform for thirty-six pulse ac–dc converter output voltage for retrofit applications

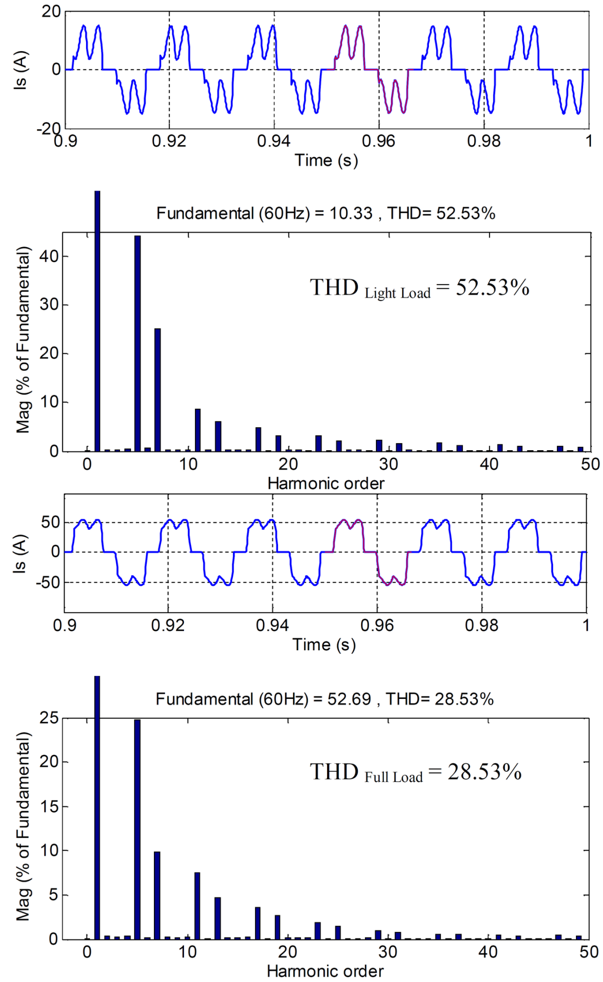

Figure 6: Input current waveform and its harmonic spectrum of six-pulse ac–dc converter at light load and full load

conditions that are not within the standard margins. Moreover, the power factor at full load is 0.937, which deteriorates to 0.848 as the load is reduced.

These results show that there is a need to improve power quality at the ac mains using harmonic mitigators, which can easily replace the existing six-pulse converter. The simulation results of different autotransformer based 36-pulse ac–dc converter fed DTCIMDs are shown in Fig. 7-9. Fig. 7 shows the waveform of the supply current along with its harmonic spectrum of tapped delta autotransformer based 36-pulse ac–dc converter fed DTCIMD at full load and light load (20%).The THD of supply current at full load is 2.20% and that at light load is 3.65%, whereas the power factor under these conditions is 0.9976 and 0.9986, respectively.

The supply current waveform along with its harmonic spectrum of polygon autotransformer based 36-pulse ac–dc converter at light load and full load is shown in Fig. 8, which shows that at full load condition, the THD of the ac mains current is 2.21% and the power factor obtained is 0.9976 and at light load condition, the THD of the ac mains current is 3.64% and the power factor is 0.9985. The supply current waveform along with its harmonic spectrum of T autotransformer based 36-pulse ac–dc converter at light load and full load is shown in Fig. 9, which shows that at full load condition, the THD of the ac mains current is 2.85% and the power factor obtained is 0.9980 and at light load condition, the THD of the ac mains current is 3.91% and the power factor is 0.9987.

Table 1: Comparison of power quality parameters of different topologies

Sr. No.	Topology	% THD of V_{ac}	AC Main-Current I_{SA}(A)		% THD of I_{SA} at		Dissortion 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	5.64	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 (tapped delta)	2.16	10.47	52.43	3.65	2.20	0.9993	0.9995	0.9993	0.9980	0.9986	0.9976	611.7	607.9
3	36-pulse (poly-gon)	2.16	10.57	52.45	3.64	2.21	0.9993	0.9995	0.9992	0.9981	0.9985	0.9976	612.7	608.9
4	36-pulse (T)	2.16	10.49	52.21	3.91	2.85	0.9992	0.9993	0.9996	0.9987	0.9987	0.9980	612.9	609.1

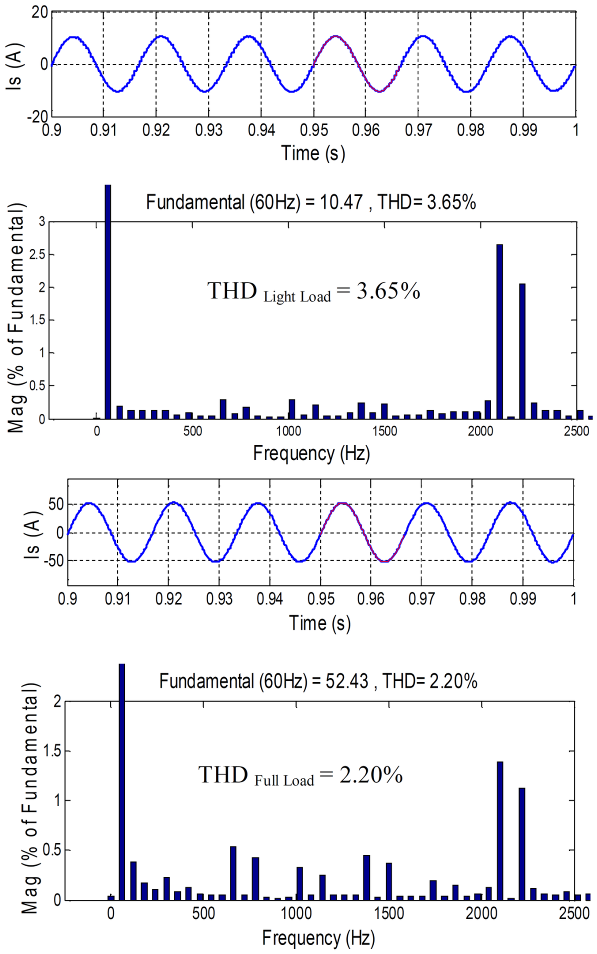

Figure 7: Input current waveform and its harmonic spectrum of tapped delta autotransformer based 36-pulse ac–dc converter at light load and full load

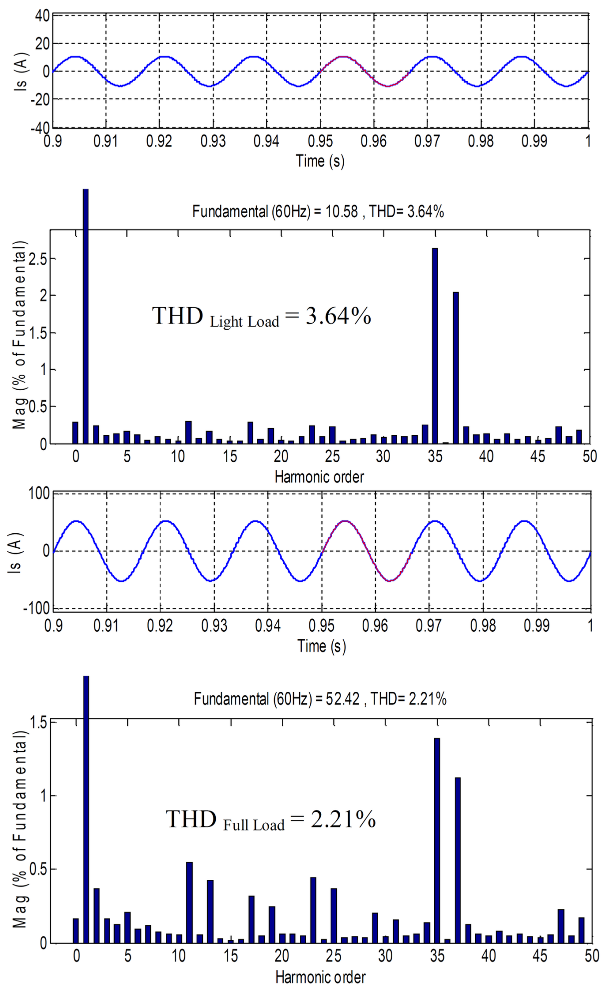

Figure 8: Input current waveform and its harmonic spectrum of polygon autotransformer based 36-pulse ac–dc converter at light load and full load

Table 1. shows a comparative study of different 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) of a DTCIMD fed from a six-pulse converter and different autotransformer based 36-pulse converters for different loading conditions. The aforementioned criteria are listed in Table 1 for the three types of converters. Results show that the input current corresponding to the different autotransformer based 36-pulse

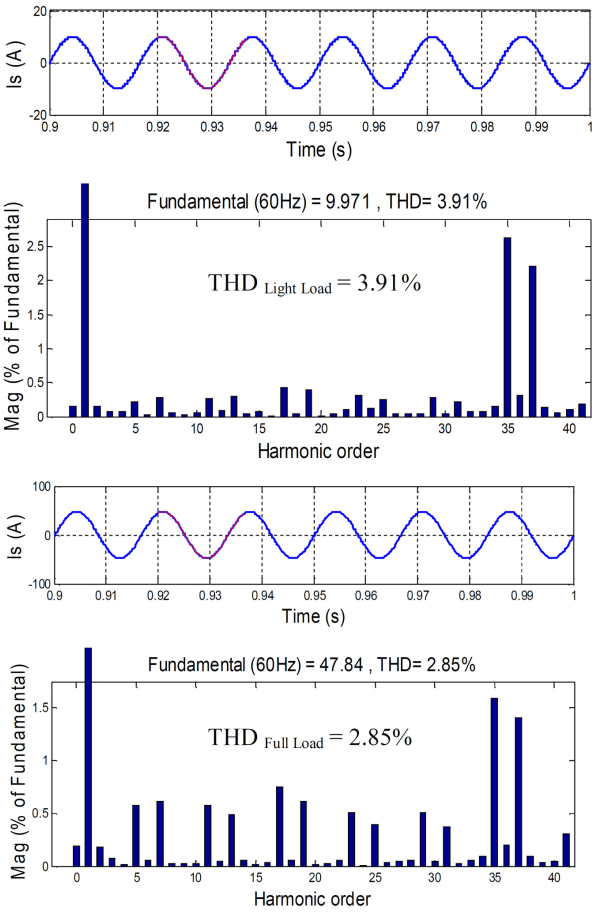

Figure 9: Input current waveform and its harmonic spectrum of T autotransformer based 36-pulse ac–dc converter at light load and full load

ac-dc converter configuration has an almost unity power factor.

The different autotransformer based 36-pulse ac–dc converters give the same dc-link voltage as that of a six-pulse diode bridge rectifier, making it suitable for retrofit applications. Furthermore, in the worst case (light loads) the current THD reached below 4% for the different autotransformer based 36-pulse ac-dc converters.

In order to verify the simulation results and the capabilities of the 36-pulse topology, a laboratory prototype of the 36-pulse converter for 10-hp load rating (Fig. 10) was built and tested using an equivalent resistive load under light load, to demonstrate the worst case conditions. The input line voltage and current waveforms and their harmonic spectrum for 36-pulse converters are measured using a HWT-1000 harmonic analyzer and shown in Figs. 11. The voltage and current THD for 36-pulse configurations are 0.5% and 4%, respectively.

5. Apparent power ratings

The apparent power (kVA) ratings of the different autotransformer and tapped IPT, for 36-pulse configuration are calculated using the following equation [4]:

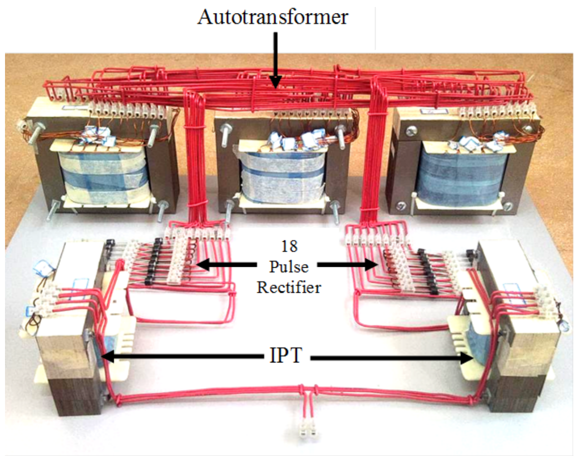

Figure 10: Laboratory prototype of 36-pulse ac-dc converter

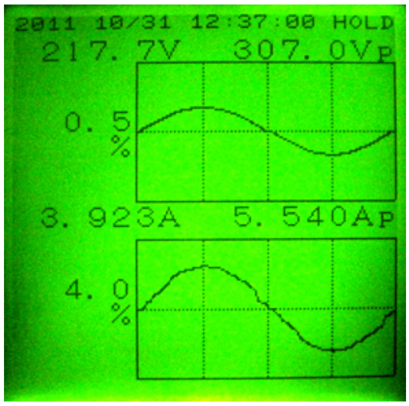

Figure 11: Input voltage and current waveform with their harmonic spectrum in experimentation for 36-pulse ac-dc conversion with light load. (10-hp load)

$$S = 0.5\Sigma V_{winding} I_{winding} \tag{1}$$

where, $V_{winding}$ is the rms voltage across each part of the autotransformer, and IPT windings and Iwinding indicate the full load current of the same windings. These rms values are obtained by simulations of 50hp (37.3 kW) load as listed in Table 2. The calculated ratings are 22904 VA and 111.9 VA for tapped delta autotransformer and IPT, respectively, which are 61.40% and 0.3% of the load power rating (37.3kW), respectively. This means that the required magnetic rating of the tapped delta topology is about 61.70% of the load rating.

The calculated ratings are 16326 VA and 58.02 VA for polygon autotransformer and IPT, respectively. The ratings of input polygon autotransformer and IPT are obtained, and these are 43.77%, and 0.15%, respectively of the load rating (37.3kW). As mentioned previously, the required magnetic rating of the polygon topology is 43.92% of the load rating. The calculated ratings are 22939VA and 149.2 VA for T autotransformer, and IPT, respectively, which are 61.5% and 0.4% of the load power rating (37.3kW), respectively. This means that the required magnetic rating of the T topology is about 61.9% of the load rating.

Table 2: Comparison of magnetic rating and cost of the 36-pulse converters based on autotransformers

Transformer Type	Main Transformer rating (% of load)	Interphase reactor rating (% of load)	Total magnetic rating (% of load)
Tapped delta 36-pulse	61.4	0.3	61.7
Polygon 36-pulse	43.77	0.15	43.92
T-connected 36-pulse	61.5	0.4	61.9

It can also be obtained from simulations that the polygon 36-pulse harmonic mitigator for retrofit applications needs all the required magnetics of 16.384 kVA to be totaled, that is to say, only 43.92% of the load power rating. Compared to the total magnetics ratings of conventional tapped delta autotransformer based 36-pulse (61.70%) and T-connected 36-pulse autotransformer (61.9%) based ac-dc converters, the total ratings of magnetics of the polygon autotransformer 36-pulse rectifier system is much lower. The detailed comparison results are tabulated in Table 2. The low equivalent kVA rating of the polygon autotransformer resulted in a system of lower volume, weight, losses and cost compared with other types of autotransformer configuration based 36-pulse ac-dc converters. These converters can be used to improve power quality in applications such as UHVDC and Photovoltaic Pumping System [23, 24].

Table 2 also presents the cost comparison of the of the 36-pulse converters. The transformer makes a major contribution to the total cost and size of the system.

The prices may vary according to market growth. The cost estimation of the transformer is made following a rule of thumb. The cost of the transformer is estimated at 5 times the kVA rating of the transformer. The different 36-pulse configurations use the same number of diodes. In different 36-pulse configurations using the same number of diodes, the polygon 36-pulse configuration is more economical than tapped delta and T connected configuration, because of the low kVA rating. The lower kVA rating of the polygon 36-pulse converter results in size and cost advantages for the polygon 36-pulse configuration.

6. Conclusions

This paper presents a comparison of tapped delta, polygon and T connected autotransformer based 36-pulse AC-DC converters. This study, based on technical and economic factors, compares different autotransformer based 36 pulse AC-DC converters. The different 36-pulse AC-DC converters are capable of eliminating up to 33rd harmonics in the input supply current. The different rectifier has the flexibility to vary the dc link voltage, simply by changing the ratio of the number of turns of the transformer, which makes it suitable for retrofit applications. The simulation results show that the THD of input current remains below 4.0% and the power factor is always above 0.998 across a wide operating range of the loads to the different autotransformer based 36-pulse ac-dc converter configuration. The low equivalent kVA rating of the polygon autotransformer results in a system of lower volume, weight, losses and cost compared with other types of autotransformer configuration based 36-pulse ac-dc converters. The improvement in power quality parameters and reduction in magnetics is considerable in the polygon autotransformer 36-pulse rectifier. Finally, the paper presents the experimental results obtained from the laboratory prototype to validate the practicability and potential prospects for utilization of the 36-pulse AC-DC converter in applications that need to comply with IEEE 519 requirements. It is evident from the experimental results that the 36-pulse AC-DC converter draws an input line current which has a THD of 4% when operating at near unity PF. On the whole, these significant characteristics of the 36-pulse AC-DC converter demonstrate that it could serve as a potential alternative for AC-DC power conversion, leading to an energy-efficient and cost-effective system.

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