Published in IET Power Electronics
Received on 9th June 2009
Revised on 22nd August 2009
doi: 10.1049/iet-pel.2009.0158

ISSN 1755-4535

Autoconnected transformer-based 18-pulse ac–dc converter for power quality improvement in switched mode power supplies

B. Singh   G. Bhuvaneswari   R. Kalpana

Department of Electrical Engineering, Indian Institute of Technology, New Delhi, India
E-mail: kal19772003@yahoo.co.in

Abstract: Switched mode power supplies (SMPS) are commonly used in telecommunication towers and welding equipments. In medium capacity SMPS, power quality at the utility interface is a major concern. A new autoconnected transformer is presented for power quality improvement in 18-pulse ac–dc converter fed SMPS with least magnetic rating. Various autoconnected transformers are studied for 18-pulse ac–dc rectification and a new autoconnected transformer is selected to improve the power quality of the supply current. The effect of load variation on SMPS is studied to demonstrate the performance and effectiveness of the proposed 18-pulse ac–dc converter-based SMPS in the wide operating range of the power supply system. A set of power quality indices at input ac mains and magnetic rating of various autoconnected transformers are presented to compare their performance. Laboratory prototype of the proposed autoconnected transformer-based 18-pulse ac–dc converter is developed and test results are presented to validate the proposed design and developed model of the converter system.

1 Introduction

Modern ac–dc converters used in telecommunication power supply are expected to draw sinusoidal input ac current at unity power factor (PF) from the utility [1, 2]. In these three-phase ac–dc converters, the ac supply voltage is rectified by a multipulse diode bridge rectifier with output filters. A high-frequency dc–dc converter yielding regulated output dc voltage is then connected between the rectifier and the load.

In order to reduce the harmonics from the utility lines, Institute of Electrical and Electronics Engineers (IEEE) has established a Standard, 519 entitled 'Recommended Practices and Requirements for Harmonics control in Electric Power Systems', in 1992 [3]. The above standard specifies permissible limits in current and voltage distortion. There have been several other standards and review articles in the literature that address power quality-related issues in ac–dc converters [4–6].

Higher pulse number-based ac–dc converters have been reported and these are simple to implement [7–13]. The use of multipulse ac–dc converters for power quality improvement have been discussed in [7] with reference to harmonic content in the input current. These converters are found to be simple, rugged and reliable. In general, these converter circuits use two or more 6-pulse converters, where the harmonics generated by each of these converters cancel each other due to phase shift. For example, an 18-pulse converter [8] eliminates harmonics of the order less than $18n \pm 1$, thus reduces the total harmonic distortion (THD) of ac mains current and improves the PF. When a multipulse converter is fed by an autoconnected transformer, it results in reduction in the magnetic rating, as each portion of this autoconnected transformer carries only a small portion of the total kVA of the output load. For applications where the demand for harmonic current reduction is more stringent, the 18-pulse rectification method is more economical than the 24-pulse rectification-based ac–dc converter, while being more effective than the 12-pulse ac–dc converter. Autoconnected transformer-based 18 pulse ac–dc converters have been reported in the literature [9] for reducing the THD of ac mains current. In this topology the dc-link voltage is higher, which are not applicable for retrofit applications. To overcome the problem of higher dc-link voltage, Hammond [10] has proposed a new topology, but the autoconnected transformer arrangement is very complex. Paice [11] has reported a new simplified autoconnected transformer topology for 18-pulse converters. But the THD of ac mains current with this topology is around 8% at full load. To reduce the THD of the input ac mains current, Kamath *et al.* [12] have also reported a new 18-pulse ac–dc converter configuration but THD of input ac mains current in this converter is varied from 6.9 to 13.1% at varying load, thus violating the limits of IEEE Standard 519-1992. Chivite-Zabalza *et al.* [13] have suggested an 18-pulse rectifier topology for retrofit applications where the transformer kVA rating is 56% of the output power rating. However, the THD of the supply current with this topology has been reported as 10.12%, which does not conform to IEEE-519 standard. Different designs for the autoconnected transformer with reduced kVA rating for multipulse converters have been reported in [14, 15]. Some of the multipulse converters may not even require interface reactors to share current equally between the rectifiers; this results in further reduction in size, weight and cost of magnetics; these are reported in the literature [16, 17].

Power supplies for telecommunication systems require galvanic isolation and stiffly regulated dc output. The challenge is to provide a suitable utility interface with a simple, efficient, low-cost and robust three-phase ac–dc converter. Seixas and Barbi [18] have suggested a high-frequency isolation technique to regulate the dc output of telecommunication power supplies with an input 18-pulse converter. An autotransformer with an interphase transformer instead of isolation of the regulated output voltage to improve the power quality of the utility line currents are discussed in the literature [19, 20]. Analysis and assessment of multipulse converters for utility interface for power electronic converter loads and aircraft applications are discussed in the literature [21, 22].

Several research papers [23–31] have discussed various multipulse ac–dc converters for power quality improvement in a variety of applications such as telecommunication power supplies, electric arc furnaces, welding power supplies and variable frequency induction motor drives. Kolar [23] and Kolar *et al.* [24] have discussed single-stage power conversion using three-phase PWM, which requires complex control, modulation and soft commutation techniques for telecommunication power supplies.

Advanced power electronics technologies such as resonant converters to eliminate the switching losses while operating at a very high switching frequency, to minimise passive component size or to employ active front end solution to improve the power quality on the input supply side for arc furnace loads, have been investigated in the literature [26, 27]. The improved three-phase power converter topologies with PF correction for a 10 kW (350 A) load using a PWM switching is reported in the literature [28] for arc welding application. Klumpner *et al.* [30, 31] have explained a novel two-stage power conversion with PF improvement in the supply current at a reduced switching frequency. An autotransformer-based multipulse ac–dc converters at the front end of vector control induction motor drive system to improve the power quality indices are explained in the literature [32–34].

In this paper various configurations of autoconnected transformers are proposed for an 18-pulse ac–dc converter that serves as the utility interface for a 12 kW (60 V/200 A) switched mode power supply (SMPS). The proposed approach is based on autoconnected transformers between the utility and diode bridge giving emphasis to reduction in magnetic ratings and to operate under varying loads on SMPS. A comparison is made among various autoconnected transformers of 18-pulse ac–dc converters in terms of different power quality indices. Based on the comparison, a delta-polygon autoconnected transformer-based 18-pulse converter is found as the best possible configuration in terms of least magnetic rating. Further, the proposed configuration reduces the harmonic current at input ac mains, which results in its low THD and also improves the PF close to unity. Hence, an experimental prototype for this configuration of autoconnected transformer is developed and various tests are conducted on this prototype to validate its design.

2 System configuration

Fig. 1 shows the schematic diagram of a 6-pulse ac–dc converter for an SMPS of 60 V/200 A load. The THD of ac mains current and PF of this converter are observed to be 26.6% and 0.9521, respectively, and it does not conform to the IEEE-519 standard. Hence, an 18-pulse ac–dc converter is proposed in this work that can bring down the THD of ac mains current and improves PF at ac mains, thereby adhering to the IEEE-519 standard requirements.

Fig. 2 shows the schematic diagram of an autoconnected transformer-based 18-pulse ac–dc converter feeding three 6-pulse diode bridge rectifiers subsequently connected to dc–dc converters. This autoconnected transformer shown in Fig. 2 can be visualised by various configurations as shown in Fig. 3*a*. The proposed system configuration uses three full bridge dc–dc converters feeding the load. A filter (L_f, C_f) is placed between the full-bridge converter and three 6-pulse diode rectifiers. Further, a high-frequency transformer at the output of the full-bridge converter provides an isolation between the primary and secondary windings. The secondary windings of the high-frequency transformers are connected in series to balance the output dc-link currents in the secondary windings. To reduce the

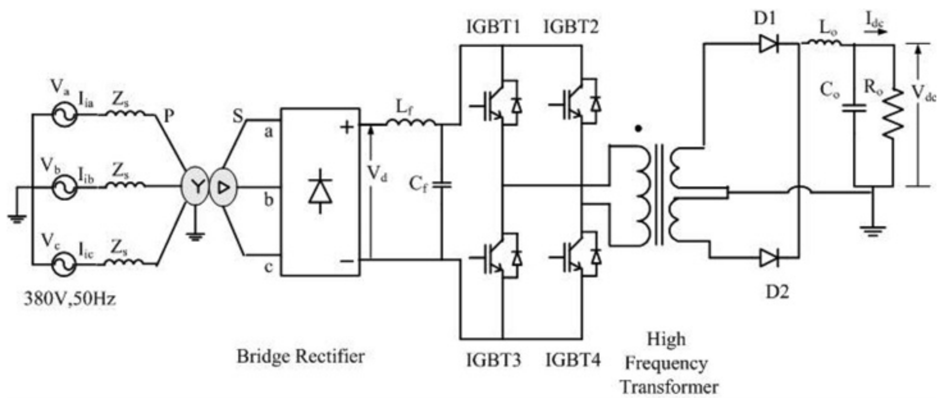


Figure 1 *Schematic diagram for a 6-pulse ac–dc converter fed SMPS*

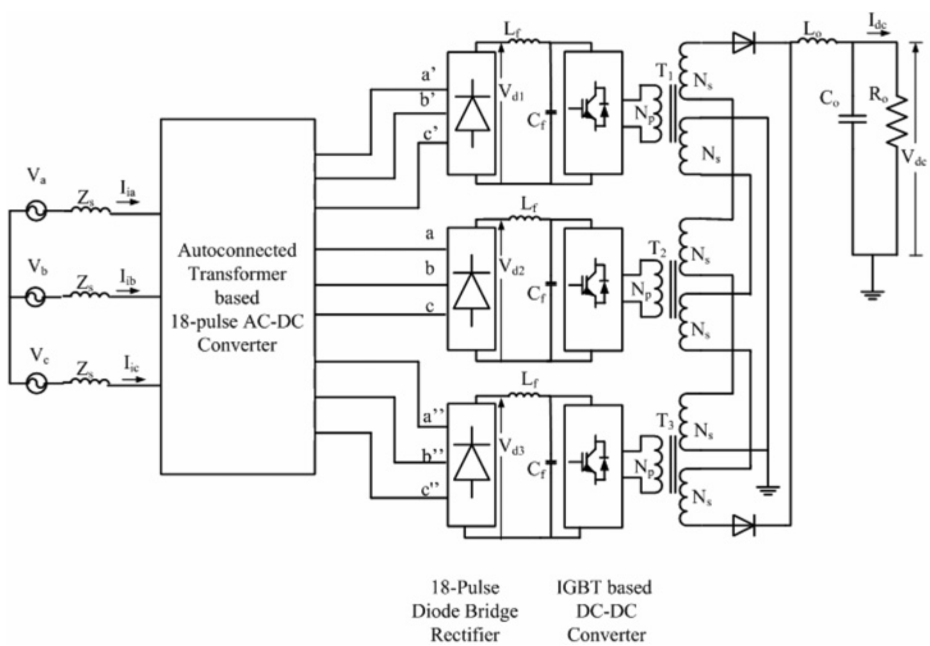
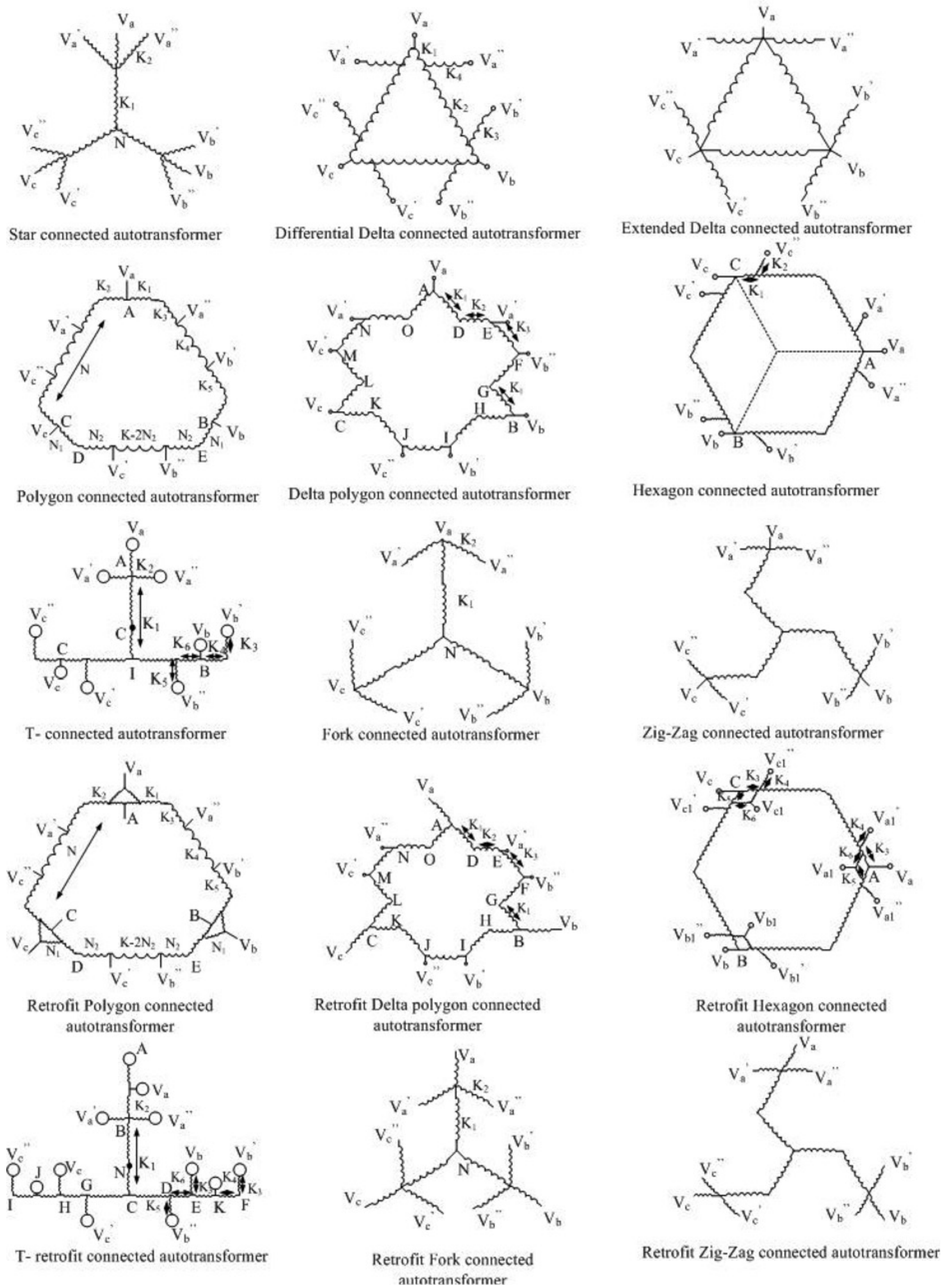


Figure 2 *Schematic diagram of autoconnected transformer-based 18-pulse ac–dc converter fed SMPS*

conduction losses in the diode, a centre tapped connection is chosen for the output rectifier. The voltage that is being rectified is the sum of the secondary windings voltages of high-frequency transformers and each secondary winding voltage corresponds to its respective dc output voltage of the 6-pulse converter. The overall output voltage represents an 18-pulse converter output consisting of the sum of three secondary windings voltages. The regulated dc output voltage is obtained through a proportional and integral (PI) controller. The converter transformer in autoconnected manner can be visualised in various configurations that would cancel out lower order harmonics, resulting in reduced THD of ac mains current. Figs. 3*a* and *b* show the winding connections of the input autoconnected transformers that are investigated for the proposed SMPS and the corresponding phasor diagrams for these configurations, respectively. It is observed that the dc-link output voltages are higher in Star, Delta, Polygon, Delta-Polygon, Hexagon, 'T', Fork and Zig-Zag autoconnected transformer-based 18-pulse ac–dc converters and are not suitable for retrofit applications. This paper proposes a cost-effective solution for retrofit applications without much alteration to the existing autoconnected transformer-based 18-pulse ac–dc converter as shown in Fig. 3*a*. In the retrofit configurations, the number of turns in each of the sections of the autoconnected transformer is adjusted such that the output dc voltage magnitude is the same as that of the original 6-pulse ac–dc converter.

3 Analysis and design

In this section, the design of an autoconnected transformer-based 18-pulse ac–dc converter is carried out for the proposed SMPS. The design methodology is developed for a number of configurations of autoconnected transformers for an 18-pulse ac–dc converter as depicted in Fig. 3*a*. The design procedure is illustrated by taking a delta-polygon autoconnected transformer configuration as an example.



a

Figure 3 *Autoconnected transformer based 18-pulse ac–dc converter configurations*

a Winding diagram for various autoconnected transformer-based 18-pulse ac–dc converter
b Phasor diagram for various autoconnected transformer-based 18-pulse ac–dc converters

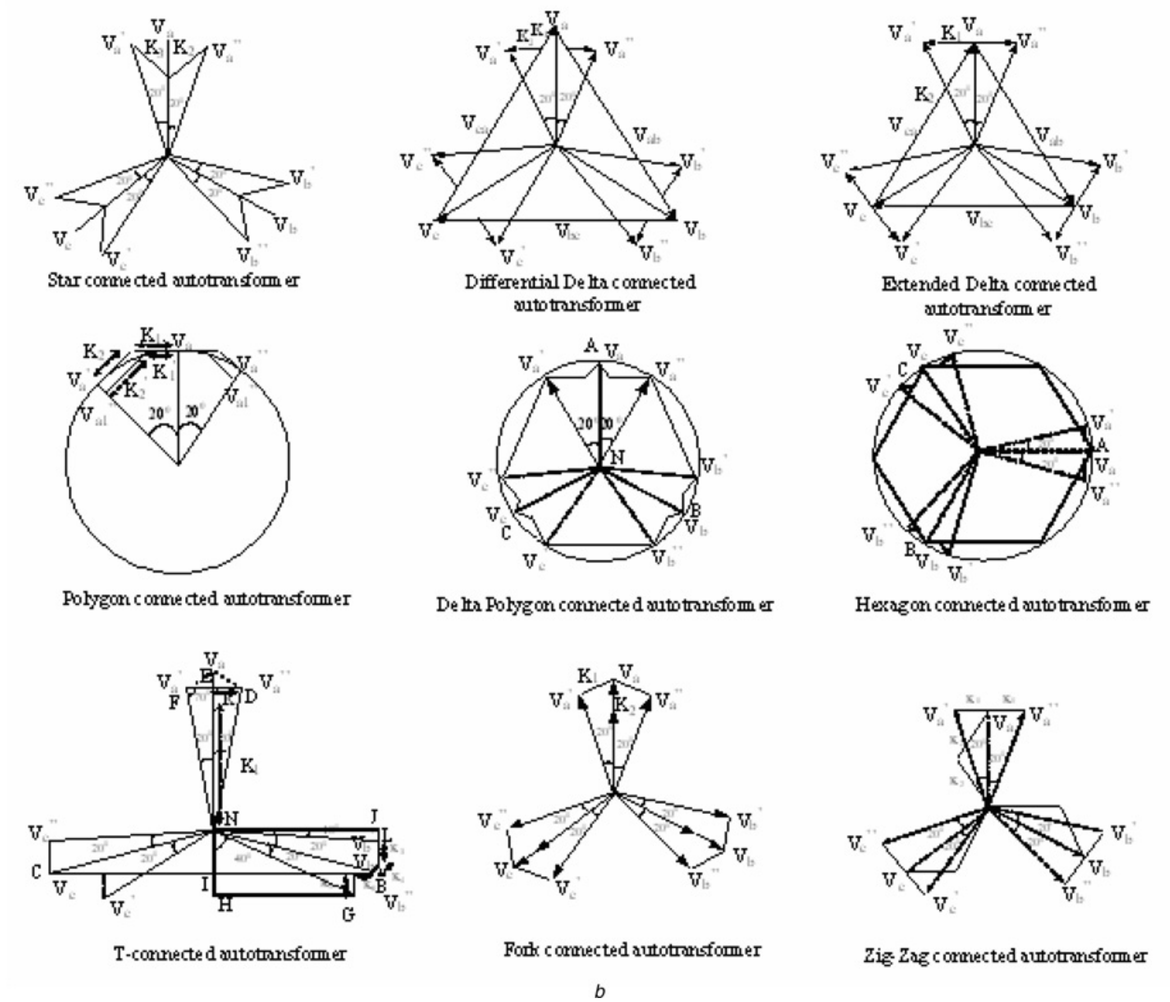


Figure 3 *Continued*

Figs. 4*a* and 4*b* show the winding and phasor diagram of delta-polygon-connected autotransformer.

3.1 Design of an autoconnected transformer

To achieve 18-pulse ac–dc converter operation, the following conditions have to be satisfied:

1. Three sets of balanced three-phase line voltages are to be produced, which are $\pm 20^\circ$ out of phase with each other.

2. The amplitude of these line voltages should be equal to each other to result in symmetrical pulses and reduced ripple in output dc voltage.

From the three-phase supply voltage, three sets of three-phase voltages have to be produced that are phase shifted from the original supply voltage by $+20^\circ$ and -20°, respectively. The number of turns required for obtaining $+20^\circ$ and -20° phase shift is calculated as follows. To find the factors K_1, K_2 and K_3, which are the measures of turns ratios of the various portions of the autoconnected transformer, consider phase 'a' voltage as shown in Figs. 4*a* and *b* as

$$V_a' = V_a - K_1 V_{ab} + K_2 V_{bc} \tag{1}$$

$$V_a'' = V_a + K_1 V_{ca} - K_2 V_{bc} \tag{2}$$

The original line to line voltage V_{ab} (as shown in Fig. 4*b*) is represented as phasor AB. Thus, the resultant phasor is given by

$$\vec{AB} = \vec{AO} + \vec{OP} + \vec{PQ} + \vec{QL} + \vec{LB} \tag{3}$$

From Fig. 4*b* the angle between OL and OR is 60°. Similarly, the angle between the OL and LM is 60°. Therefore $OP = QL = V \times K_2 \cos 60^\circ$, $PQ = V \times K_3$ and $AO = LB = V \times K_1$. In normalised form (3) is expressed as

$$1 = K_1 + K_2 \cos 60^\circ + K_3 + K_2 \cos 60^\circ + K_1 \tag{4}$$

It reduces as

$$2K_1 + K_2 + K_3 = 1 \tag{5}$$

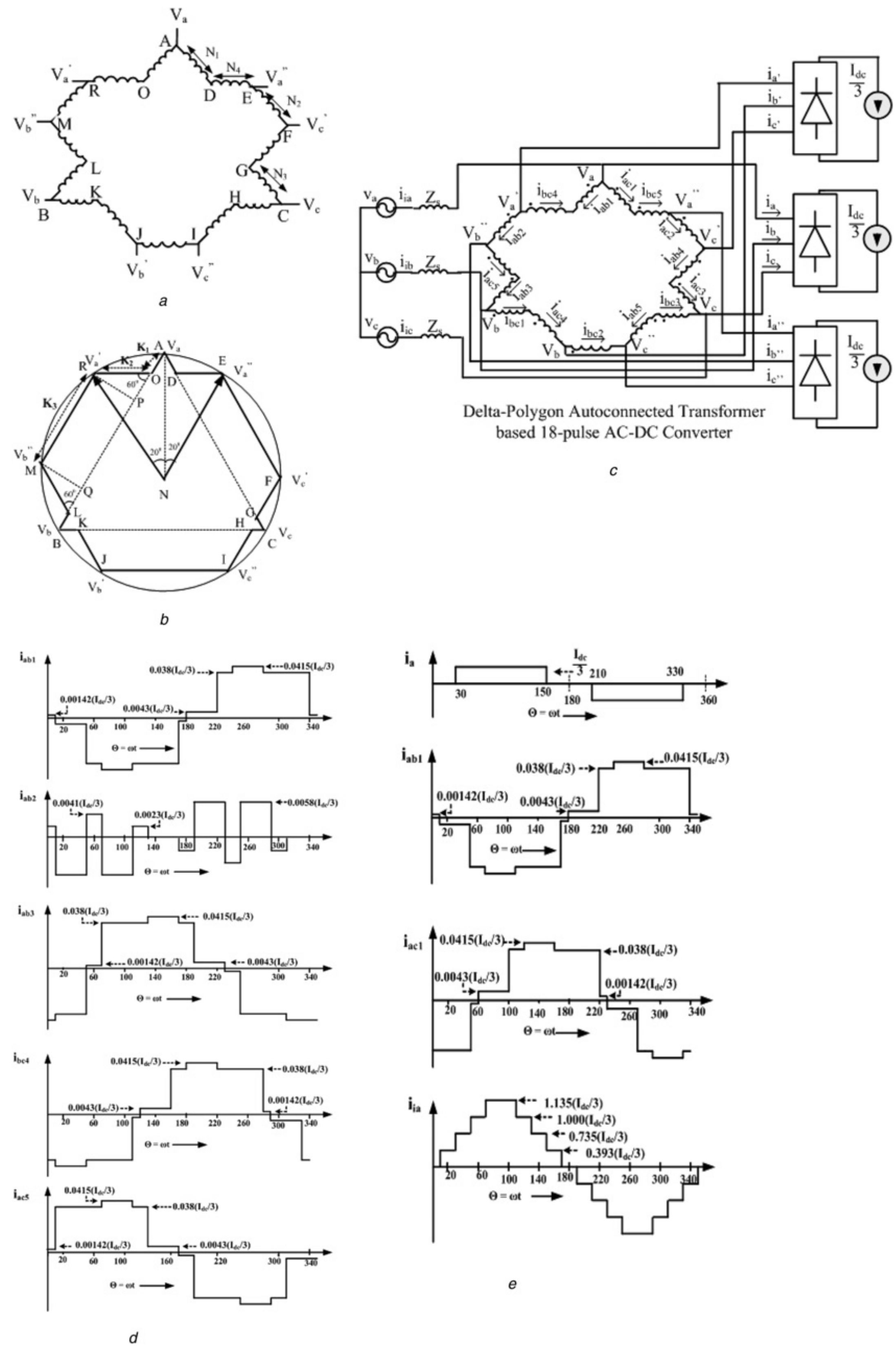


Figure 4 *Analysis of the proposed delta-polygon autoconnected transformer configuration and its waveforms*

a Winding diagram of delta-polygon autoconnected transformer
b Phasor diagram of delta-polygon autoconnected transformer
c Simplified circuit for delta-polygon autoconnected transformer-based 18-pulse ac–dc converter
d Winding currents of a delta-polygon autoconnected transformer-based 18-pulse ac–dc converter between phases 'a' and 'b'
e Input current (i_a) of three-phase diode bridge, winding currents (i_{ab1} and i_{ac1}) and input line current (i_{ia}) of a delta-polygon autoconnected transformer-based 18-pulse ac–dc converter

The following are the three-phase voltages in $+20^\circ$ and -20° phase shifted form

$$V_a = V\angle 0^\circ, \quad V_b = V\angle -120^\circ, \quad V_c = V\angle 120^\circ \tag{6}$$

$$V'_a = V\angle 20^\circ, \quad V'_b = V\angle -100^\circ, \quad V'_c = V\angle 140^\circ \tag{7}$$

$$V''_a = V\angle -20^\circ, \quad V''_b = V\angle -140^\circ, \quad V''_c = V\angle 100^\circ \tag{8}$$

where V is the rms value of phase voltage.

Substituting (6)–(8) into (1) and (2) the value of K_1 and K_2 are found to be 0.04026 and 0.157, respectively, for the desired phase shift in the autoconnected transformer outputs. Therefore substituting values of K_1 and K_2 in (5) the value of K_3 is 0.762.

Thus, the phase-shifted voltages for phase 'a' are

$$V'_a = V_a - 0.04026V_{ab} + 0.157V_{bc} \tag{9}$$

$$V''_a = V_a + 0.04026V_{ca} - 0.157V_{bc} \tag{10}$$

A phase shifted voltage is obtained through connecting original phase voltage V_a to the following:

1. Tapping a portion (0.04026) of line voltage V_{ab} and

2. Connecting one end of an approximately (0.157) of line voltage V_{bc} to this tap.

Thus the autoconnected transformer can be designed with these constants viz. K_1, K_2 and K_3. Similarly, the phase shifted voltages are obtained for other autoconnected transformer configurations. The number of turns for each winding of the autoconnected transformer can be calculated from the above constants and these are given in the Appendix.

3.2 Analysis of autoconnected transformer connection

A detailed analysis of the winding currents and voltages to find the magnetic rating of delta-polygon connected 18-pulse ac–dc converter is done in this section. Fig. 4c shows the simplified diagram of a delta-polygon autoconnected transformer-based 18-pulse ac–dc converter configuration for the analysis of winding currents. For the analysis, it is considered that the output of the diode-bridge rectifier is connected to a constant dc load current and the input ac mains consist of balanced voltages. Moreover, it is considered that each diode-bridge carries 1/3 of the dc load current ($I_{dc}/3$). The currents flowing through each winding for a delta-polygon autoconnected transformer are shown in Fig. 4c. It is considered that the current flowing between phases 'a' and 'b' is i_{ab}. Similarly, the current flowing between phases 'b' and 'c' is i_{bc} and the current flowing between phases 'c' and 'a' is i_{ac}. The waveforms of winding currents, input diode-bridge current and the input line current are shown in Figs. 4d and e.

The winding currents in each phase flow through two sections of the winding, main and auxiliary windings. Main winding current components i_{ab1}, i_{ab2}, i_{ab3} are the currents in the winding sections between phases 'a' and 'b'. Auxiliary winding current components i_{ab4} and i_{ab5} are considered to be part of the winding between phases 'a' and 'b' as shown in Fig. 4c. The values of these current components are computed in terms of dc load current (I_{dc}). In addition, the currents i_{bc4} and i_{ac5} in the remaining two windings (which are connected between the phases 'b' and 'c' and 'a' and 'c', respectively) are also obtained to estimate ac mains current. The waveforms of these currents are shown in Fig. 4d and it is observed that the magnitude and shape of the currents (i_{ab1}, i_{ab3}, i_{bc4}, i_{ac5}) are similar in nature but each is phase shifted from the other by 60° (i.e. the phase shift between i_{ab1} and i_{bc4}, and also i_{ab3} and i_{ac5} is 60°). The rms values of these winding currents are represented as follows

$$I_{ab1,rms} = I_{ab3,rms} = I_{bc4,rms} = I_{ac5,rms} \tag{11}$$

$$I_{ab1,rms} = \sqrt{(1/2\pi)\int_0^{2\pi} i^2_{ab1}(t)\mathrm{d}(\omega t)} \tag{12}$$

$$I_{ab2,rms} = \sqrt{(1/2\pi)\int_0^{2\pi} i^2_{ab2}(t)\mathrm{d}(\omega t)} \tag{13}$$

The magnitude levels of the current components shown in Figs. 4d and e are obtained from the simulation by considering $I_d/3$ (i.e. 200/3 = 66.67 A) as reference value. The simulation is carried out for negligible leakage reactance value of the autoconnected transformer. Using these magnitudes from the current waveform and from (12) and (13), the rms currents through the windings between phases 'a' and 'b' in terms of dc load current (I_{dc}) can be calculated as

$$I_{ab1,rms} = \left[\left(\frac{80}{180}(0.038)^2 + \frac{40}{180}(0.0415)^2 + \frac{20}{180}(0.00142)^2 + \frac{40}{180}(0.0043)^2\right)\left(\frac{\pi}{10}\right)\right]^{1/2}\left(\frac{I_{dc}}{3}\right) = 0.0454I_{dc} \tag{14}$$

$$I_{ab2,rms} = \left[\left(\frac{40}{180}(0.0023)^2 + \frac{80}{180}(0.0058)^2 + \frac{20}{180}(0.0041)^2\right) \times \left(\frac{\pi}{10}\right)\right]^{1/2}\left(\frac{I_{dc}}{3}\right) = 0.0059I_{dc} \tag{15}$$

The rms voltage across each winding of the autoconnected transformer is obtained as a product of line rms voltage ($V_{LL,\ rms}$) and their corresponding turns ratio (K_1, K_2 and K_3). Thus, the rms voltages across the windings between phases 'a' and 'b' are given as follows

$$V_{\mathrm{ab1,rms}} = V_{\mathrm{ab3,rms}} = K_1 V_{\mathrm{LL,rms}} \tag{16}$$

$$V_{\mathrm{ab2,rms}} = K_3 V_{\mathrm{LL,rms}} \tag{17}$$

$$V_{\mathrm{bc4,rms}} = V_{\mathrm{ac5,rms}} = K_2 V_{\mathrm{LL,rms}} \tag{18}$$

In general, for any 'n' pulse converter the average voltage from output of the rectifier (V_{dc}) in terms of line rms voltage is calculated from (19)

$$V_{\mathrm{dc}} = (n/2\pi)\int_{-\pi/n}^{+\pi/n} \sqrt{2}V_{\mathrm{LL,rms}}\cos(\omega t)\mathrm{d}(\omega t) \tag{19}$$

where 'n' is the number of pulses of an ac–dc converter. For an 18-pulse converter $n = 18$, therefore the average dc output voltage is obtained as follows

$$\begin{aligned} V_{\mathrm{dc}} &= (9/\pi)\int_{-\pi/18}^{+\pi/18} \sqrt{2}V_{\mathrm{LL,rms}}\cos(\omega t)\mathrm{d}(\omega t) \\ &= 1.407V_{\mathrm{LL,rms}} \end{aligned} \tag{20}$$

The VA rating of the autoconnected transformer (S_{rating}) in terms of line rms voltage and output dc current is calculated by summing the product of rms voltage and rms current in each winding and halving the result and which is computed as follows [1]

$$S_{\mathrm{rating}} = 0.5\left(\sum V_{\mathrm{rms}} I_{\mathrm{rms}}\right) \tag{21}$$

$$\begin{aligned} &= 0.5(3)[2(V_{\mathrm{ab1,rms}}I_{\mathrm{ab1,rms}}) + (V_{\mathrm{ab2,rms}}I_{\mathrm{ab2,rms}}) \\ &\quad + 2(V_{\mathrm{ac5,rms}}I_{\mathrm{ac5,rms}})] \\ &= 0.5(3)[2(0.04026V_{\mathrm{LL,rms}} \times 0.0454I_{\mathrm{dc}}) \\ &\quad + (0.762V_{\mathrm{LL,rms}} \times 0.0059I_{\mathrm{dc}}) \\ &\quad + 2(0.157V_{\mathrm{LL,rms}} \times 0.0454I_{\mathrm{dc}})] \\ &= 0.033V_{\mathrm{LL,rms}}I_{\mathrm{dc}} \end{aligned} \tag{22}$$

Considering line rms voltage, $V_{\mathrm{LL,rms}} = 380$ V, and output dc current, $I_{\mathrm{dc}} = 200$ A. Thus, the VA rating of the autoconnected transformer is found to be

$$S_{\mathrm{rating}} = 2.508\,\mathrm{kVA} \tag{23}$$

Therefore the autoconnected transformer magnetic rating (S_{rating}) as a fraction of the output load power, P_{dc} (12 kW) can be obtained as

$$S_{\mathrm{rating}} = \frac{2.508}{12.0}P_{\mathrm{dc}} = 0.209P_{\mathrm{dc}} = 0.209V_{\mathrm{dc}}I_{\mathrm{dc}} \tag{24}$$

where $P_{\mathrm{dc}} = V_{\mathrm{dc}}I_{\mathrm{dc}}$.

Thus, the magnetic rating of the autoconnected transformer is found to be approximately 21% of the load for a delta-polygon autoconnected transformer-based 18-pulse ac–dc converter configuration. Similarly, the magnetic ratings of all other autoconnected transformer configurations are calculated as described in the above procedure and these values are tabulated in Table 1. It is observed that the magnetic rating of a delta-polygon autoconnected transformer-based 18-pulse ac–dc converter configuration is the least, as compared to other configurations, hence resulting in reduced cost of magnetics.

From Fig. 4e it is observed the diode-bridge current i_{a} conducts for a period of 120° starting from 30°. The waveforms of the remaining currents i_{b} and i_{c} are also similar with a phase shift of 120° between each other. From Fig. 4c, the input line current $i_{i\mathrm{a}}$ for the delta-polygon autoconnected transformer-based 18-pulse ac–dc converter is obtained by applying Kirchoff's current law at node 'a' and it is given as follows

$$i_{i\mathrm{a}} = i_{\mathrm{ab1}} + i_{\mathrm{ac1}} + i_{\mathrm{a}} \tag{25}$$

where i_{ab1} is the winding currents between phases 'a' and 'b' and i_{ac1} is the winding currents between phases 'a' and 'c'.

The THD of input line current is calculated by the relationship between the rms value of the input line current and the rms value of the fundamental frequency component of the input line current. These values are obtained by analysing the input line current ($i_{i\mathrm{a}}$) waveform. Using the magnitudes from the current waveform as shown in Fig. 4e and by (26) the rms value of the input line current ($I_{i\mathrm{a,rms}}$) is calculated from quarter wave symmetry as

$$I_{i\mathrm{a,rms}} = \sqrt{(2/\pi)\int_0^{\pi/2} i_{i\mathrm{a}}^2(t)\mathrm{d}(\omega t)} \tag{26}$$

$$\begin{aligned} I_{i\mathrm{a,rms}} &= \left[\frac{2}{\pi}\left(\int_{\pi/18}^{\pi/6}(0.393)^2\mathrm{d}(\omega t) + \int_{\pi/6}^{5\pi/18}(0.735)^2\mathrm{d}(\omega t)\right.\right. \\ &\quad + \int_{5\pi/18}^{7\pi/18}(1.000)^2\mathrm{d}(\omega t) \\ &\quad \left.\left. + \int_{7\pi/18}^{\pi/2}(1.135)^2\mathrm{d}(\omega t)\right)\right]^{1/2}\left(\frac{I_{\mathrm{dc}}}{3}\right) \\ &= \left[\frac{2}{\pi}((0.393)^2 + (0.735)^2 + (1.000)^2\right. \\ &\quad \left. +(1.135)^2)\left(\frac{\pi}{9}\right)\right]^{1/2}\left(\frac{I_{\mathrm{dc}}}{3}\right) \end{aligned}$$

$$I_{i\mathrm{a,rms}} = 0.8142\left(\frac{I_{\mathrm{dc}}}{3}\right) \tag{27}$$

From Fig. 4e it is realised that the input line current has quarter wave symmetry. Hence all the even harmonics are absent and the cosine term in the Fourier series expansion

Table 1 Comparison of magnetic rating and power quality indices for various autoconnected transformer-based 18-pulse ac–dc converters

Sl. no.	Autoconnected transformer configuration	kVA rating	kVA rating in terms of P_{dc}	DPF	DF	PF	THD, %
1	Star	2.987	0.2489	0.9934	0.9989	0.9943	4.69
2	Delta	2.894	0.2416	0.9821	0.9996	0.9817	4.94
3	Extended Delta	2.785	0.2313	0.9835	0.9988	0.9824	4.89
4	Polygon	2.697	0.2248	0.9888	0.9998	0.9886	4.35
5	Delta-Polygon	2.512	0.2093	0.9893	0.99913	0.9884	4.06
6	Hexagon	2.611	0.2175	0.9840	0.9992	0.9832	4.87
7	‘T’ Connection	2.829	0.2358	0.9889	0.9996	0.9885	4.66
8	Fork	2.705	0.2254	0.9846	0.999	0.9836	4.47
9	Zig-Zag	2.899	0.2408	0.9856	0.9912	0.9847	4.21
10	Retrofit Polygon	2.704	0.2253	0.9863	0.9995	0.9858	4.46
11	Retrofit Delta-Polygon	2.657	0.2214	0.9965	0.9995	0.996	4.58
12	Retrofit Hexagon	2.713	0.2261	0.9871	0.9995	0.9866	5.02
13	Retrofit ‘T’ connected	2.846	0.2372	0.9893	0.9998	0.9891	4.78
14	Retrofit Fork	2.753	0.2294	0.9924	0.9993	0.9843	4.53
15	Retrofit Zig-Zag	2.943	0.2452	0.9911	0.9953	0.9864	4.35

is zero. Thus, the amplitude of the fundamental frequency component of the input line current ($I_{1ia,\max}$) is calculated as

$$\begin{aligned}
I_{1ia,\max} &= (4/\pi)\int_0^{\pi/2} i_{ia}\ \sin(\omega t)\mathrm{d}(\omega t)\\
&= \left[\frac{4}{\pi}\left(\int_{\pi/18}^{\pi/6}(0.393)\sin(\omega t)\mathrm{d}(\omega t)\right.\right.\\
&\quad + \int_{\pi/6}^{5\pi/18}(0.735)\sin(\omega t)\mathrm{d}(\omega t)\\
&\quad + \int_{5\pi/18}^{7\pi/18}(1.000)\sin(\omega t)\mathrm{d}(\omega t)\\
&\quad \left.\left. + \int_{7\pi/18}^{\pi/2}(1.135)\ \sin(\omega t)\mathrm{d}(\omega t)\right)\right]\\
&= \left[\frac{4}{\pi}(0.8997)\right]\left(\frac{I_{dc}}{3}\right) \qquad (28)
\end{aligned}$$

$$I_{1ia,\max} = 1.1455\left(\frac{I_{dc}}{3}\right) \qquad (29)$$

The rms value of the fundamental frequency component of the input line current ($I_{1ia,\mathrm{rms}}$) is calculated as follows

$$\begin{aligned}
I_{1ia,\mathrm{rms}} &= \frac{I_{1ia,\max}}{\sqrt{2}} \qquad (30)\\
&= \frac{1.1455}{\sqrt{2}}\left(\frac{I_{dc}}{3}\right)\\
&= 0.8099\left(\frac{I_{dc}}{3}\right) \qquad (31)
\end{aligned}$$

The THD of input line current is calculated as

$$\%i_{\mathrm{THD}} = \frac{\sqrt{I_{ia,\mathrm{rms}}^2 - I_{1ia,\mathrm{rms}}^2}}{I_{1ia,\mathrm{rms}}} \times 100 \qquad (32)$$

Substituting the values of $I_{1ia,\mathrm{rms}}$ and $I_{ia,\mathrm{rms}}$ in (32), % THD of input ac mains current is obtained as

$$\%i_{\mathrm{THD}} = 10.32\%$$

Thus, the theoretical value of i_{THD} for an 18-pulse ac–dc converter is found to be 10.32%. The distortion factor (DF) is calculated from (33)

$$\mathrm{DF} = \frac{1}{\sqrt{(1+\mathrm{THD}^2)}} = 0.9947 \qquad (33)$$

4 MATLAB-based simulation

An 18-pulse ac–dc converter fed SMPS is simulated in MATLAB environment along with SIMULINK and Sim Power System (SPS) toolboxes, as shown in Fig. 5*a*. This model shows a three-phase supply of 380 V, 50 Hz connected to the 18-pulse ac–dc converter, which employs the autoconnected transformer for creating three sets of three-phase voltages as shown in Fig. 5*b*. It shows the three-phase multiwinding interconnections in the autoconnected transformer that feed supply to the 18-pulse ac–dc converter. This 18-pulse ac–dc converter is connected to the dc-link that feeds dc power to full bridge dc–dc converters. The full bridge dc–dc converter is connected to the high-frequency transformer which is connected to a dc load of 12 kW (60 V/200 A) SMPS. The output voltage is regulated by a PI controller. The parameters used in the simulation of the 18-pulse ac–dc converter fed SMPS are given in the Appendix. The simulation is carried out for all the 18-pulse ac–dc converter configurations shown in Fig. 3*a* for the same supply and load conditions to compare their performances. Table 1 shows the performance indices for various autoconnected transformer-based 18-pulse ac–dc converter.

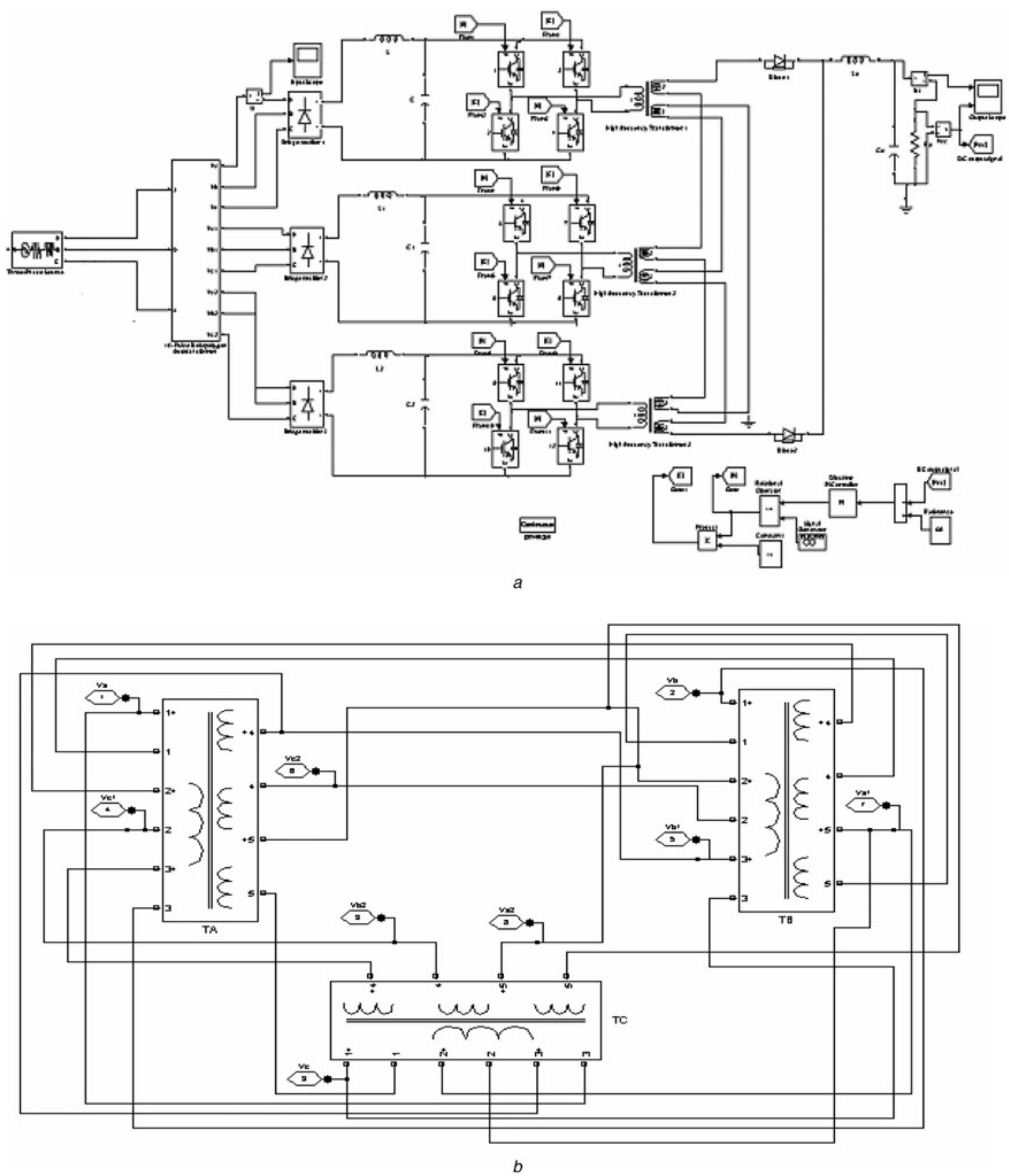


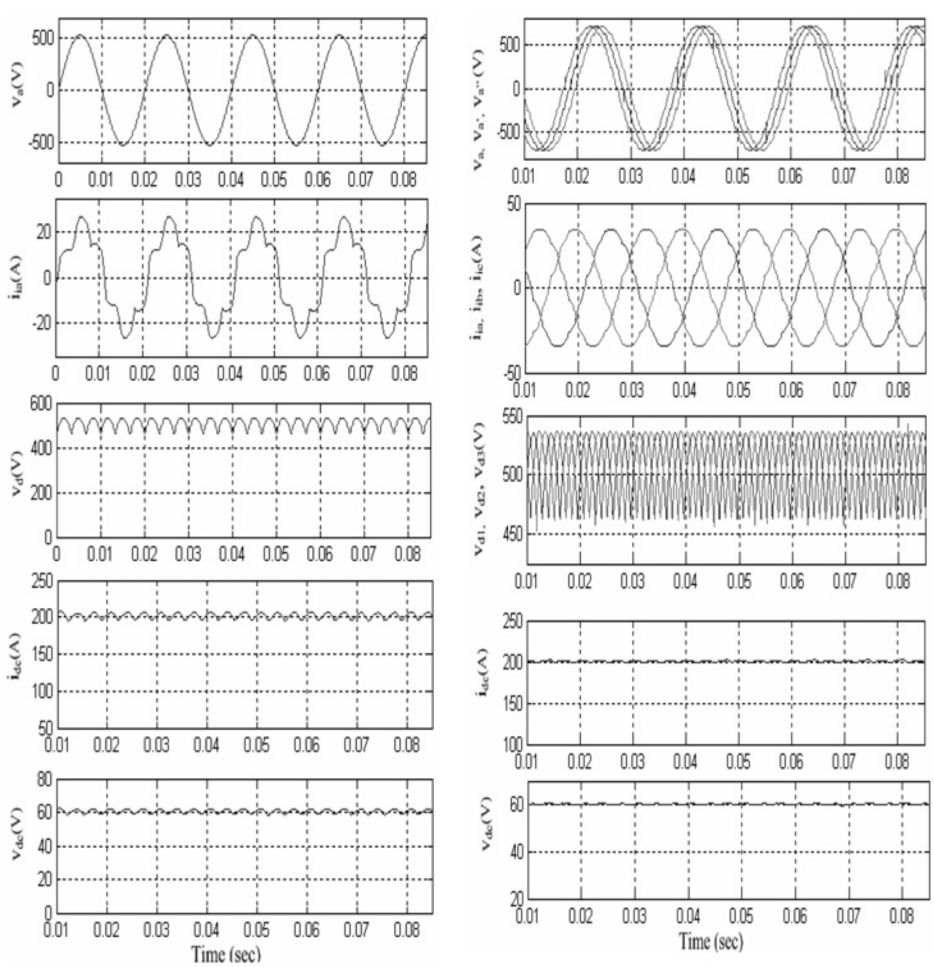
Figure 5 *Simulation model of the proposed 18-pulse ac–dc converter fed SMPS*

a MATLAB model block diagram for delta-polygon autoconnected transformer-based 18-pulse ac–dc converter fed SMPS
b MATLAB model block diagram for delta-polygon autoconnected transformer-based 18-pulse ac–dc converter

The simulated results for 6-pulse and delta-polygon autoconnected transformer-based 18-pulse ac–dc converters are shown in Fig. 6. The input currents/voltages, dc-link currents/voltages are shown in these figures. The variations of THD and PF for different values of leakage reactance for the delta-polygon autoconnected transformer-based 18-pulse ac–dc converter are shown in Figs. 7*a* and *b*, respectively. The leakage reactance of the autoconnected transformer is nominally considered as 5% while simulating various converter configurations. The variation of THD of ac mains current with varying loads is shown in Fig. 7*c*.

5 Experimentation

To validate the design and modelling of these converters, a delta-polygon autoconnected transformer-based 18-pulse ac–dc converter is developed in the laboratory and simulated results are verified on this experimental prototype. Three single-phase transformers are designed and wound in the laboratory as per the design details given in the Appendix. The numbers of turns are calculated based on the voltage across the windings. Similarly, the gauge of the wire is calculated based on the current flowing through the windings. Tests are conducted at the input line voltage of 110 V with balanced resistive load across each of the 6-pulse bridge converters. Extensive tests are conducted on the developed prototype and the results recorded using the Fluke power analyser 43B are presented here. Figs. 8 and 9 show both the simulated and experimental results. Fig. 8 shows the results of input currents ($i_{a'}$, i_a and $i_{a'}$) to the diode bridge rectifier and winding voltages/currents of a delta-polygon autoconnected transformer-based 18-pulse ac–dc converter. Fig. 9 shows the input current waveform along with its harmonic spectrum and THD for a 6-pulse ac–dc converter and a delta-polygon autoconnected based 18-pulse ac–dc converter. The effects of load variation on power quality indices for a delta-polygon autoconnected transformer-based 18-pulse ac–dc converter are given in Table 2.



a b

Figure 6 *Simulated waveforms for the 6-pulse and the proposed 18-pulse ac–dc converters*

a Simulated waveforms of input voltage/current, dc-link voltage/current and output voltage/current of a 6-pulse ac–dc converter fed SMPS
b Simulated waveforms of input voltage/current, dc-link voltage/current and output voltage/current of a delta-polygon autoconnected transformer-based 18-pulse ac–dc converter fed SMPS

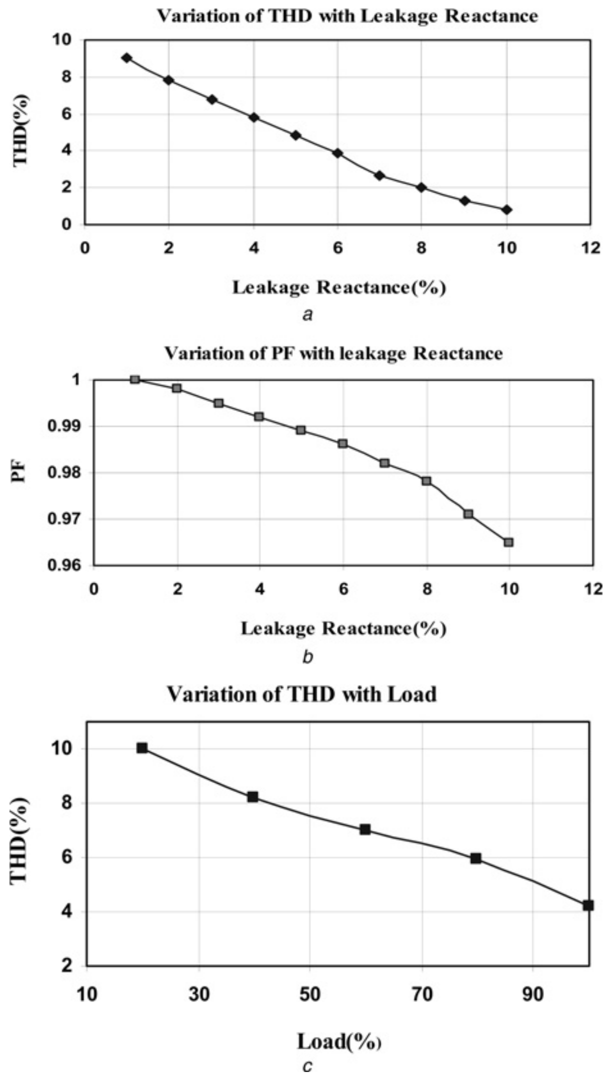


Figure 7 *Variation of power quality indices with leakage reactance and load*

a Variation of THD of ac mains current with leakage reactance of a delta-polygon autoconnected transformer-based 18-pulse ac–dc converter
b Variation of PF with leakage reactance of a delta-polygon autoconnected transformer-based 18-pulse ac–dc converter
c Variation of THD of ac mains current with load of a delta-polygon autoconnected transformer-based 18-pulse ac–dc converter

6 Results and discussion

A 6-pulse ac–dc converter along with the SMPS is simulated to demonstrate the performance of the system. The input voltage/current, output voltage/current waveform of a 6-pulse ac–dc converter for a 60 V/200 A load is shown in Fig. 6*a*. The simulated and experimental results of input current waveform along with its frequency spectrum and THD for a 6-pulse ac–dc converter are shown in Fig. 9*a*. It is observed that THD of ac mains current for a 6-pulse ac–dc converter is 26.60% in simulation and 22.5% in experimentation. Moreover, the displacement power factor (DPF) and PF are found to be 0.9754 and 0.9521, respectively. These results show that there is a need for improving the power quality at input ac mains by using a multipulse ac–dc converter, which can replace the existing 6-pulse ac–dc converter.

To improve the THD of ac mains current and PF, an 18-pulse ac–dc converter feeding a 12 kW SMPS circuit is designed and its performance is simulated to study its behaviour. The simulated performance of various autoconnected transformer-based 18-pulse ac–dc converters configurations for a 12 kW load is presented in Table 1. It is observed from this table that a delta-polygon autoconnected transformer-based 18-pulse ac–dc converter results in the least kVA rating and also the best possible THD of ac mains current and PF values as compared to other configurations. It needs an autoconnected transformer of 2.512 kVA; the magnetic rating is only 21% of the SMPS load rating. It further results in saving in space, volume, size and finally the cost of the power supply. It is also observed that the PF remains above 0.98 and the THD of ac current is reduced to 4.06%. Further, it is observed from Table 1 that the PF is better for the star and the retrofit delta-polygon autoconnected transformer configurations than the proposed delta-polygon autoconnected transformer, but the magnetic rating is approximately 2–4% more. So it can be said that a specific configuration can be chosen for a particular application depending upon whether it is important to maintain the PF close to unity or to reduce the magnetic rating of the autoconnected transformer. The supply current waveform along with the harmonic spectra for a delta-polygon autoconnected transformer-based 18-pulse ac–dc converter at full load and light load condition is shown in Figs. 9*b* and *c*, respectively. The waveform of input ac mains current has improved drastically in the delta-polygon autoconnected transformer-based 18-pulse converter. The presence of some sub-harmonic content in the ac mains current can be observed in the experimental result in Fig. 9*c*, whereas they are absent in the simulated result for the same case. This may be attributed to small deviations in the supply frequency and imbalance in the three-phase source impedances. This can cause variations in the source impedance perceived by the converters and may result in amplification of certain sub-harmonic contents in the current waveform. The improvement of other power quality indices in the 18-pulse converter has also been observed at various loads as presented in Table 2. The power quality indices obtained from the simulation of the delta-polygon autoconnected transformer-based 18-pulse ac–dc converter at varying loads are found to match with the experimental results as depicted in Table 2. Test result shows that i_{THD} (THD of ac mains current) at full load has improved considerably resulting in a value within 5%. The v_{THD} of input voltage waveform has also improved to the order of less than 5%. It shows that the value of THD of ac mains current varies from 4 to 10% with varying loads for a delta-polygon autoconnected transformer-based 18-pulse ac–dc converter. This meets IEEE-519 standard requirements of power quality.

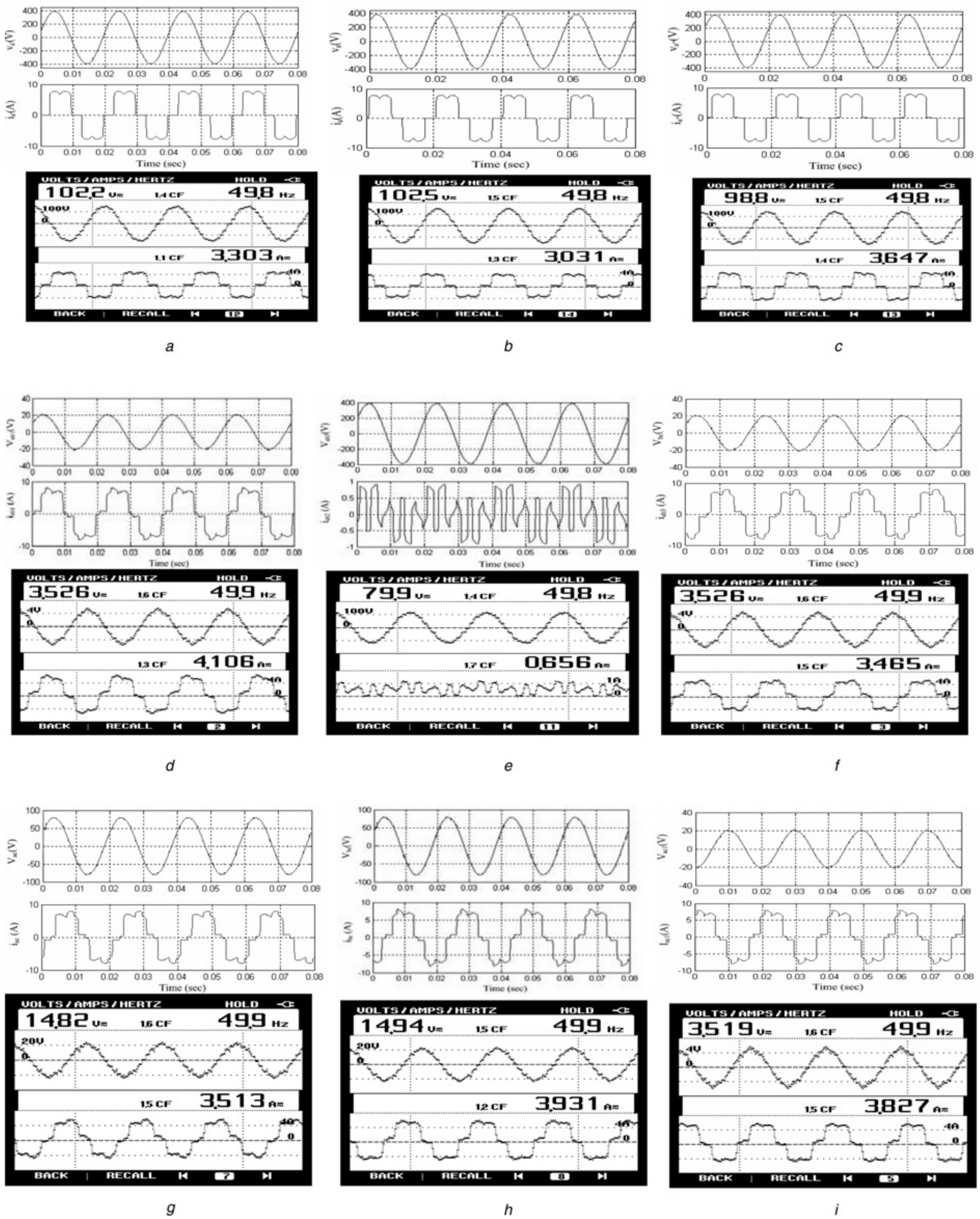
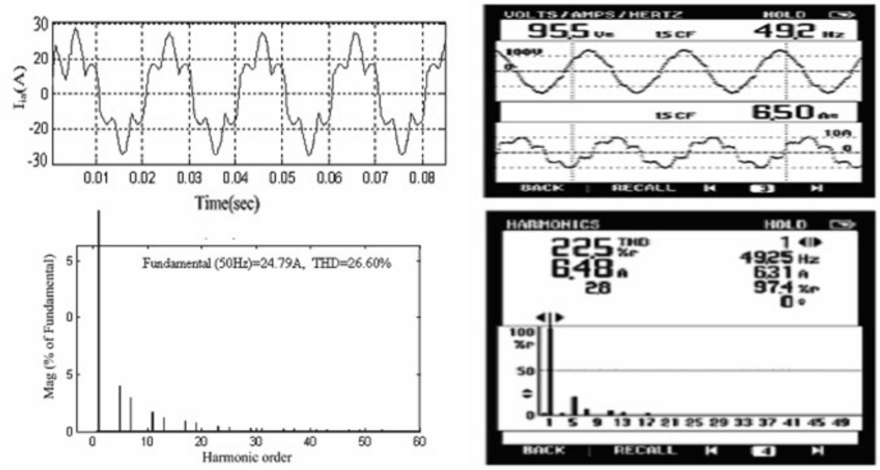
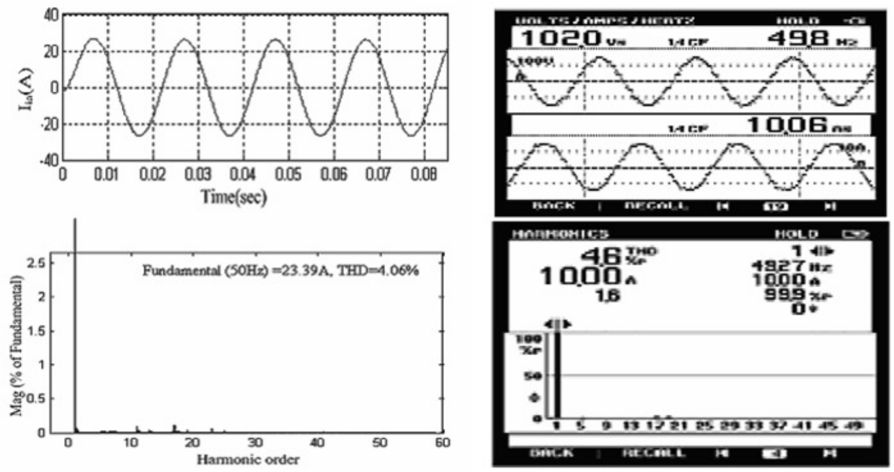


Figure 8 *Simulation and test results of winding voltages and currents of a delta-polygon autoconnected transformer-based 18-pulse ac–dc converter in reference Fig. 4c*

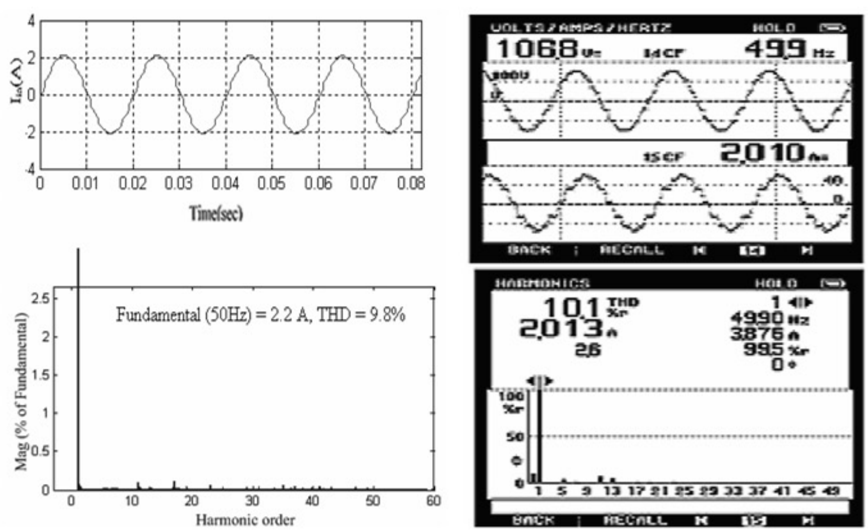
a Waveforms of current component $i_{a'}$
b Waveforms of current component i_a
c Waveforms of current component $i_{a''}$
d Waveforms of current component i_{ab1}
e Waveforms of current component i_{ab2}
f Waveforms of current component i_{ab3}
g Waveforms of current component i_{ac}
h Waveforms of current component i_{bc}
i Waveforms of current component i_{ac1}



a



b



c

Figure 9 *Simulation and test results for the 6-pulse and the proposed 18-pulse ac–dc converter fed SMPS*

a Simulation and test results of input mains current i_{ia} along with its harmonic spectrum and THD for a 6-pulse ac–dc converter at full load
b Simulation and test results of input mains current i_{ia} along with its harmonic spectrum and THD for a delta-polygon autoconnected transformer-based 18-pulse ac–dc converter at full load
c Simulation and test results of input mains current i_{ia} along with its harmonic spectrum and THD for a delta-polygon autoconnected transformer-based 18-pulse ac–dc converter at light load (20%)

Table 2 Effect of load variation on power quality indices of a delta-polygon autoconnected transformer-based 18 pulse ac–dc converter

Load, %	THD, %) input current (i_{THD})	THD, % input voltage (v_{THD})	DF	DPF	PF	THD, % input current (i_{THD})	THD, % input voltage (v_{THD})	DF	DPF	PF
	Simulation results					Experimental results				
20	9.8	1.7	0.9952	0.9879	0.9846	10.1	1.9	0.9949	0.9883	0.9833
40	7.9	2.0	0.9968	0.9882	0.9852	8.2	2.6	0.9966	0.9878	0.9845
60	6.3	2.8	0.9960	0.9887	0.9865	6.9	3.4	0.9976	0.9894	0.9870
80	5.2	3.7	0.9986	0.9891	0.9878	5.8	4.2	0.9983	0.9901	0.9885
100	4.1	4.0	0.9991	0.9893	0.9884	4.6	4.4	0.9989	0.9903	0.9894

Figs. 7*a* and *b* show the variation of i_{THD} and PF with leakage reactance, respectively. It is evident that as leakage reactance increases, harmonic content of the input current reduces but PF deteriorates. The variation of i_{THD} with varying load is presented in Fig. 7*c*.

The calculated and the simulated values of the current THD in the ac mains are 10.32 and 4.06%, respectively. The difference in these two values can be attributed to the difference in the leakage reactance values of the autoconnected transformer considered for the calculated case and the simulation model. While calculating the THD analytically, the transformer is considered to have negligible leakage reactance whereas in the simulation model it is considered to have a finite value of leakage reactance. This results in commutation overlap and hence brings down the value of input current THD in the simulated results.

Fig. 8 shows both the simulation and experimental results of input current to the diode bridges and winding currents/voltages of the 18-pulse ac–dc converter autoconnected transformer, which are found to match with the analytical results fairly well. In this figure the experimental results obtained through test are also similar to those obtained through simulation results. The simulation and test results of input mains current waveform along with its harmonic spectrum for the delta-polygon autoconnected transformer-based 18-pulse ac–dc converter are shown in Figs. 9*b* and *c* at full load and light load conditions, respectively. The simulated and the experimental results show similar trends, thus validating the developed design procedure and simulation model of the delta-polygon autoconnected transformer-based 18-pulse ac–dc converter.

7 Conclusions

An 18-pulse ac–dc converter with various autoconnected transformer configurations has been designed, modelled, simulated and developed for an SMPS. The comparison of various autoconnected transformer configuration shows that the delta-polygon autoconnected transformer-based 18-pulse ac–dc converter results in a saving of about 3–4% in terms of magnetic ratings as well as cost. An experimental prototype has also been developed for the proposed delta-polygon autoconnected transformer-based 18-pulse ac–dc converter, which has yielded the best possible results in terms of the magnetic rating and power quality indices. From test results, it is evident that power quality has significantly improved by employing this configuration for an 18-pulse ac–dc converter feeding an SMPS. Test results have shown that the THD of input current remains below 5% and the PF remains above 0.98, which meets the requirements of IEEE-519 standard. Based on these results, it is concluded that the proposed converter has resulted in improved THD and PF close to unity.

8 References

[1] PAICE D.A.: 'Power electronic converter harmonic multipulse methods for clean power' (IEEE Press, New York, 1996)

[2] PRESSMAN A.I.: 'Switching power supply design' (McGraw-Hill, International Editions, New York, 1999)

[3] IEEE Recommended Practices and Requirements for Harmonics control in Electric Power Systems, IEEE Standard, 519, 1992

[4] Limits for Harmonic current Emissions, International Electrotechnical Commission Standard 61000–3-2, 2004

[5] SINGH B., SINGH B.N., CHANDRA A., AL-HADDAD K., PANDEY A., KOTHARI D.P.: 'A review of three-phase improved power quality ac–dc converters', *IEEE Trans. Ind. Electron.*, 2004, **51**, (3), pp. 641–660

[6] SINGH B., GAIROLA S., SINGH B.N., CHANDRA A., AL-HADDAD K.: 'Multipulse AC–DC converters for improving power quality: a review', *IEEE Trans. Power Electron.*, 2008, **23**, (1), pp. 260–281

[7] KAMATH G.R.: 'Autotransformer-based system and method of current harmonic reduction in a circuit'. U.S. Patent No. 6861936, 1 March 2005

[8] OGUCHI K., YAMADA T.: 'Novel 18-step diode rectifier circuit with non-isolated phase shifting transformers', *Proc IEE Electric Power Appl.*, 1997, **144**, (1), pp. 1–5

[9] PAICE D.A.: 'Optimized 18-pulse type ac–dc or dc–ac converter system'. U.S. Patent No. 5124904, 23 June 1992

[10] HAMMOND P.W.: 'Autotransformer'. U.S. Patent No. 5619407, 8 April, 1997

[11] PAICE D.A.: 'Transformer for multiple AC/DC converters'. U.S. Patent No. 6101113, 8 August 2000

[12] KAMATH G.R., BENSON D., WOOD R.: 'A novel autotransformer based 18-pulse rectifier circuit'. IEEE APEC Conf., December 2002, vol. 2, pp. 795–801

[13] CHIVITE-ZABALZA F.J., FORSYTH A.J., TRAINER D.R.: 'Analysis and practical evaluation of an 18 pulse rectifier for aerospace applications'. Proc. IEEE PEMD Conf., April 2004, pp. 338–343

[14] GUIMARAES C., OLIVIER G., APRIL G.E.: 'High current ac/dc power converters using T-connected transformers'. Proc. IEEE Canadian Conf. ECE, 5–8th September 1995, pp. 704–707

[15] CHOI S., ENJETI P.N., PITEL I.J.: 'Polyphase transformer arrangements with reduced kVA capacities for harmonic current reduction in rectifier type utility interface', *IEEE Trans. Power Electron.*, 1996, **11**, (5), pp. 680–690

[16] LIXIANG W., GUSKOV N., LUKASZEWSKI R.A., SKIBINSKI G.L.: 'Mitigation of current harmonics for multipulse diode front end rectifier systems', *IEEE Trans. Ind. Appl.*, 2007, **43**, (3), pp. 787–797

[17] KIM S., ENJETI P.N., PACKBUSH P., PITEL I.J.: 'A new approach to improve power factor and reduce harmonics in a three-phase diode rectifier type utility interface', *IEEE Trans. Ind. Appl.*, 1994, **30**, (6), pp. 1557–1564

[18] DE SEIXAS F.J.M., BARBI I.: 'A 12 KW three-phase low THD rectifier with high-frequency isolation regulated DC output', *IEEE Trans. Power Electron.*, 2004, **19**, (2), pp. 371–377

[19] MARTINS D.C., OLIVERIA A.H.D., BARBI I.: 'Three-phase rectifier using a SEPIC DC–DC converter in continuous conduction mode for power factor correction'. Proc. IEEE INTELEC'98, 4–8th October 1998, pp. 491–497

[20] MUNOZ C.A.B., BARBI I.: 'A new high power-factor three phase AC–DC converter; analysis, design and experimentation', *IEEE Trans. Power Electron.*, 1999, **4**, (1), pp. 90–97

[21] HAHN J., ENJETI P.N.: 'A wide input range multipulse 3 phase rectifier for utility interface of power electronics converter'. Proc. IEEE Industry Applications Conf., October 2002, vol. 4, pp. 2514–2519

[22] UAN-ZO-LI A., WANG F., BOROYEVICH D., LACAUX F., TARDY C.A.: 'Comparison of prospective topologies for aircraft autotransformer-rectifier units'. Proc. IEEE IECON, November 2003, vol. 2, pp. 1121–1127

[23] KOLAR J.W.: 'Status of the techniques of the three phase rectifier system with low effects on the mains'. Proc. INTELEC Conf., 1999, pp. 338–343

[24] KOLAR J.W., DROFENIK U., ZACH F.C.: 'Vienna rectifier II – a novel single stage high frequency isolated three-phase PWM rectifier'. Proc. APEC Conf., 1998, vol. 1, pp. 23–33

[25] UAN-ZO-LI A., BURGOS R.P., LACAUX F., WANG F., BOROYEVICH D.: 'Analysis of new step-up and step-down 18-pulse direct symmetric autotransformer-rectifiers units'. Proc. IEEE Industry App. Conf., October 2005, vol. 1, pp. 145–152

[26] NOGUCHI T., NISHIYAMA K., ASAI Y., MATSUBARA T.: 'Development of 13-V, 5000-A dc power supply with high-frequency transformer coupling applied to electric furnace'. Proc. Int. Conf. Power Electron Drives Systems, November 2005, vol. 2, pp. 1474–1479

[27] LADOUX P., POSTIGLIONE G., FOCH H., NUNS J.: 'A comparative study of AC/DC converter for high-power DC arc furnance'. Proc. IEEE APEC'05, March 2005, pp. 254–259

[28] BLASCO N., MARTINEZ A., PEREZ CEBOLLA F.J., VICUNA J.E., LACAMARA I., OLIVA J.A.: 'Evaluation of power converter for MMA arc welding'. Proc IEEE Int. Symp. Ind. Electron., June 2007, pp. 365–370

[29] JI-QIANG H., SHU-JUN C., SHU-YAN Y., DONG-PING W., HUA Z.: 'A novel three-phase welding inverter power supply with high power factor'. Proc. IEEE Industrial Technology, 2003, vol. 2, pp. 1113–1118

[30] KLUMPNER C.: 'A new two-stage voltage source inverter with modulated DC-link voltage and reduced switching losses'. Proc. IEEE IECON'06, 2006, pp. 2208–2213

[31] KLUMPNER C., CORBRIDGE M.: 'A two-stage power converter for welding applications with increased efficiency and reduced filtering'. Proc. IEEE ISIE'08, July 2008, pp. 251–256

[32] SINGH B., BHUVANESWARI G., GARG V.: 'An 18 pulse AC–DC converter for power quality improvement in vector

controlled induction motor drives', *Proc. IEE Electric Power Appl.*, 2006, **153**, pp. 88–96

[33] SINGH B., BHUVANESWARI G., GARG V.: 'A novel magnetic solution for harmonic mitigation in varying rectifier loads', *Jr. Inst. Eng. (India)*, 2006, **87**, pp. 8–11

[34] SINGH B., GAIROLA S., CHANDRA A., AL-HADDAD K.: 'Zig-zag connected autotransformer based controlled ac–dc converter with pulse multiplication'. Proc. IEEE Int. Symp. Ind. Electron. ISIE, Vigo, Spain, 4–7th June 2007, pp. 889–894

9 Appendix

9.1 Converter specifications

Input supply voltage: 380 V, 50 Hz.

Source impedance: 3%.

DC output power: 12 kW (60 V/200 A).

Switching frequency: 35 kHz.

DC-link parameters: $L_f = 4$ mH, $C_f = 1.3$ μF.

Output inductor, capacitor: $L_o = 15$ μH, $C_o = 4000$ μF.

High-frequency transformer specifications:

Primary turn, $N_p = 14$ turns.

Secondary turn, $N_s = 1$ turn.

Controller parameters:

PI controller $K_p = 50$; $K_i = 0.3$.

9.2 Physical design and construction of the autoconnected transformer

The autoconnected transformer is made up of three single transformers T_A, T_B and T_C as per the following details:

Leakage inductance for each phase winding is 0.05 p.u.

Resistance for each phase of winding is 0.005 p.u.

Magnetising inductance L_m and magnetising resistance R_m is 200 p.u for each phase winding.

Transformer winding details:

Winding number of turns (gauge of wire)

24(SWG = 13), 547(SWG = 21), 24(SWG = 13), 103(SWG = 13), 103(SWG = 13).

Transformer design details:

Flux density: 0.8 T.

Current density: 2.3 A/mm^2.

Turn per volt: 1.

Core size:

E-laminations: length = 184.1 mm, width = 171.4 mm.

I-laminations: length = 171.4 mm, width = 50.8 mm.

Area of cross-section of core: 3225 mm^2 (50.8 mm × 63.5 mm).

Core number: number 8.