An Improved 24-Pulse Rectifier for Harmonic Mitigation in More Electric Aircraft

Abdollahi, Rohollah ; B. Gharehpetian, Gevork; Anvari-Moghaddam, Amjad; Blaabjerg, Frede

Published in:
IET Power Electronics

DOI (link to publication from Publisher):
10.1049/pel2.12168

Publication date:
2021

Document Version
Publisher's PDF, also known as Version of record

Received: 18 February 2021 | Revised: 11 May 2021 | Accepted: 14 June 2021

DOI: 10.1049/pel2.12168

The Institution of Engineering and Technology WILEY

ORIGINAL RESEARCH PAPER

An improved 24-pulse rectifier for harmonic mitigation in more electric aircraft

R. Abdollahi[1] | **G. B. Gharehpetian**[2] | **A. Anvari-Moghaddam**[3] | **F. Blaabjerg**[3]

[1] Electrical Engineering Department, Technical and Vocational University, Qom, Iran

[2] Electrical Engineering Department, Amirkabir University of Technology, Tehran, Iran

[3] Department of Energy Technology, Aalborg University, Aalborg, Denmark

Correspondence
Rohollah Abdollahi, Electrical Engineering Department, Technical and Vocational University, Qom, Iran.
Email: roholla.abdollahi@yahoo.com

Abstract

To increase the power rating and reduce the cost and complexity of a multi-pulse rectifier (MPR), it is well known that the pulse number must be increased. In some practical cases, a 12-pulse rectifier (12PR) is suggested as a good solution considering its relatively simple structure and low weight. However, 12-pulse rectifiers cannot technically meet the standards of harmonic distortion requirements for some industrial applications, and therefore they must be used along with output filters. Two cost-effective 24-pulse rectifiers (24PRs) are suggested in the article, which consist of a polygon autotransformer 12PR and two pulse doubling circuits (PDCs) at dc link. The first PDC (PDC1) is based on an interphase transformer (IPT) with a step-up secondary winding, and the second one (PDC2) is based on an IPT with a step-down secondary winding. To show the advantages of the proposed combinations compared with other solutions, simulation results are used, and also a prototype is implemented to evaluate and verify the simulation results. The simulation and experimental test results show that the total harmonic distortion (%THD) of the input current for the 12PR with PDC1 is less than 3.67%, and the 12PR with PDC2 is less than 1.45%, which meets the IEEE 519 and DO-160G requirements. Also, it is shown that in comparison with other solutions, the proposed two configurations are cost-effective, power factor is near unity, rating is almost 29% of the load rating, and the efficiency is almost 97.5%, which makes them a practical solution for more electric aircraft.

1 | INTRODUCTION

To improve power quality at the point of common coupling (PCC), various topologies of multi-pulse rectifiers (MPRs) have been presented and implemented in different industrial applications. Also, they have widely been applied due to their simple configuration, low total harmonic distortion (%THD), robustness, and power factor correction capability [1–3]. Although diverse designs of 12- and 18-pulse rectifiers have been suggested to reduce the %THD of the input current [4, 5], some of them still cannot meet the recommendations and requirements of well-known standards [6, 7]. For instance, without using any output filters, the %THD of the input current of the 12-pulse rectifier (12PR) will be about 15%, which cannot meet the IEEE [6] and IEC [7] standards, and also DO-160G [8], which is used for testing airborne equipment for the entire spectrum of aircraft. To overcome this problem, researchers have proposed various auxiliary circuits for the dc or ac sides of MPRs [9–11]. In [12, 13], various 24PRs have been suggested based on 12PRs with active harmonic mitigation at the dc link. However, the proposed designs have problems with control strategies, and would add computational burden, and should also solve accuracy problems in measuring the main control variables, which in turn results in reliability reduction and higher costs.

To handle this issue, many researchers have used much higher pulse numbers, namely 40- and 72-pulse rectifiers with passive harmonic mitigation on dc side [14–18]. But this approach is undesirable when a considerable number of MPRs must be used in an industrial application. In this case, many transformers with high turn ratios must be used. Therefore, they would have large winding dimensions and high core weight, and also considerable high rating. In [19], to enhance the PCC power quality, a transformer-based 24PR based on passive harmonic mitigation has been suggested. However, the major drawback of the transformer-based MPRs is its magnetic parts significant rating, which may be more than 100% of dc load rating. Therefore, the selection of an autotransformer-based 12PR with harmonic mitigation is a logical option considering its lower weight, transformer structure simplicity, low power rating, and fewer losses. Also, in non-isolated applications, the multi-phase autotransformer design must be used for 12PR, due to their lower rating in comparison with conventional transformers. In order to reduce current %THD and improve power quality indexes, passive harmonic mitigation circuits are suggested in the dc-link, because their design is simple and they do not need any control system.

Another approach is the application of an 18-pulse autotransformer rectifier unit (ATRU), which can have a shifting angle of 20°, 40°, and 37° [20]. As discussed in [21], 18-pulse ATRUs have very good capabilities for MEA applications. However, in this paper, two new MPR will be suggested, which have a lower kVA rating (30% of the load rating) in comparison with other solutions and it does not need application of any filter to satisfy DO-160G, which results in a good alternative to MEA applications.

In recent years, some pulse harmonic reduction circuits (PHRCs) on the dc side of 12PRs with good properties were proposed [22–26]. In [27], the dc side harmonic reduction methods of parallel-connected 12PRs have accurately been classified. Considering the above-mentioned advantages, a 12PR is suggested in this paper, which is based on a simple autotransformer with a low rating. This design is connected to two simple pulse doubling circuits (PDCs) with low ratings, in order to obtain two 24PR for more electric aircraft applications. It must be noticed that the merit of the PDC1 in comparison with the conventional PDC is the use of an inter-phase transformer (IPT) with a step-up secondary winding. This winding acts as a step-up transformer and results in a voltage increase and current decrease, which in turn reduces the current passing through PDC diodes and conduction losses, and therefore the suggested structure can be used in applications with high current loads. The IPT used in the conventional PDC [14–18] has only one winding, and the diodes are connected to this winding. Therefore, the load current flows through the PDC1 diodes, and as a result the conduction losses are considerable. Also, for high current loads, the rating of the didoes used should be high enough, which increases the costs.

To improve the performance of the proposed 24-pulse rectifier and further reduce the harmonic distortion of the input current, another PDC (PDC2) is presented in this paper. Unlike the first PDC (PDC1), PDC2 has an IPT with a step-down secondary winding, which leads not only to a slight increase in kVA rating and an increase in connection losses, but also greatly reduces the input current %THD. The proposed 24PR using PDC2 can meet the requirements of the MIL-STD 1399 standard (input current %THD less than 3%).

In sum, to tackle the mentioned difficulties, i.e. poor power quality, high rating, complex control, and high cost and size, this paper presents two cost-effective solutions, which are based on the application of two PDCs at the dc-link of an autotransformer-based 12PR.

The contributions of this paper are as follows:

- The suggested design uses a retrofit polygon autotransformer, which meets all technical constraints, and in comparison with other options, has less rating, weight, volume, and cost.
- In the suggested 24PRs, two PDCs at a dc-link of 12PR are used, which have good technical capabilities and lower ratings.
- In the PDC1, an IPT is employed, which has a step-up secondary winding and four diodes. This solution leads to a reduction in input current %THD to less than 5%, which satisfies IEEE-519 requirements and conduction losses of diodes.
- In the PDC2, an IPT is employed, which has a step-down secondary winding and four diodes. This solution leads to a reduction in input current %THD to less than 3%, which satisfies the MIL-STD 1399 requirements.
- In the introduced rectifiers, two PDCs are applied to the 12PR dc-link; it has good technical capabilities and a lower rating for eliminating the harmonics as per DO-160G without any need for a filter.

2 | PROPOSED 24PRS TOPOLOGY

The two proposed 24PR are depicted in Figure 1. As mentioned, it is based on a 12PR and two PDC. The 12PR consists of a retrofit polygon autotransformer, which generates two sets of three-phase voltage with a 30° phase shift. Also, it has two 6-pulse diode bridge rectifiers (DBRs), and a zero sequence blocking transformer (ZSBT), which plays an important role in this rectifier. In the case of the utilization of an MPR for isolating the phase shift transformers, the application of the ZSBT is not necessary. However, the ZSBT must be used here to guarantee the independent operation of the autotransformer output voltages, because the retrofit polygon autotransformer has been used in this paper. The ZSBT eliminates the voltage difference between two DBRs and suppresses the circulating current to ensure an independent operation of two 6-pulse DBRs. As it can be seen in Figure 1, in order to increase the pulse number of the 12PR, the PDC is used and connected to the dc-link of the 12PR.

In Figure 1a, The PDC1, using an IPT with a step-up secondary winding, and in Figure 1b, The PDC1, using an IPT with a step-down secondary winding. Unlike conventional PDCs, the IPT in PDC1 has an additional step-up secondary winding to reduce the diodes current, which results in a decrease in the IPT secondary winding power flow rate. Reducing the current rating through the four diodes reduces the dual-circuit losses compared to conventional PDC arrays, and increases the ability to use dual-circuit arrays for heavy loads. The relationship between the load voltage and the secondary winding of the IPT determines the number of pulses based on a diode bridge. The voltage in the secondary winding of the IPT and the load voltage are supposed to be equal to u_s and u_d, respectively. As shown in Figure 2, and considering the relationship between u_s and u_d, the rectifier of the PDC1 has three operation modes.

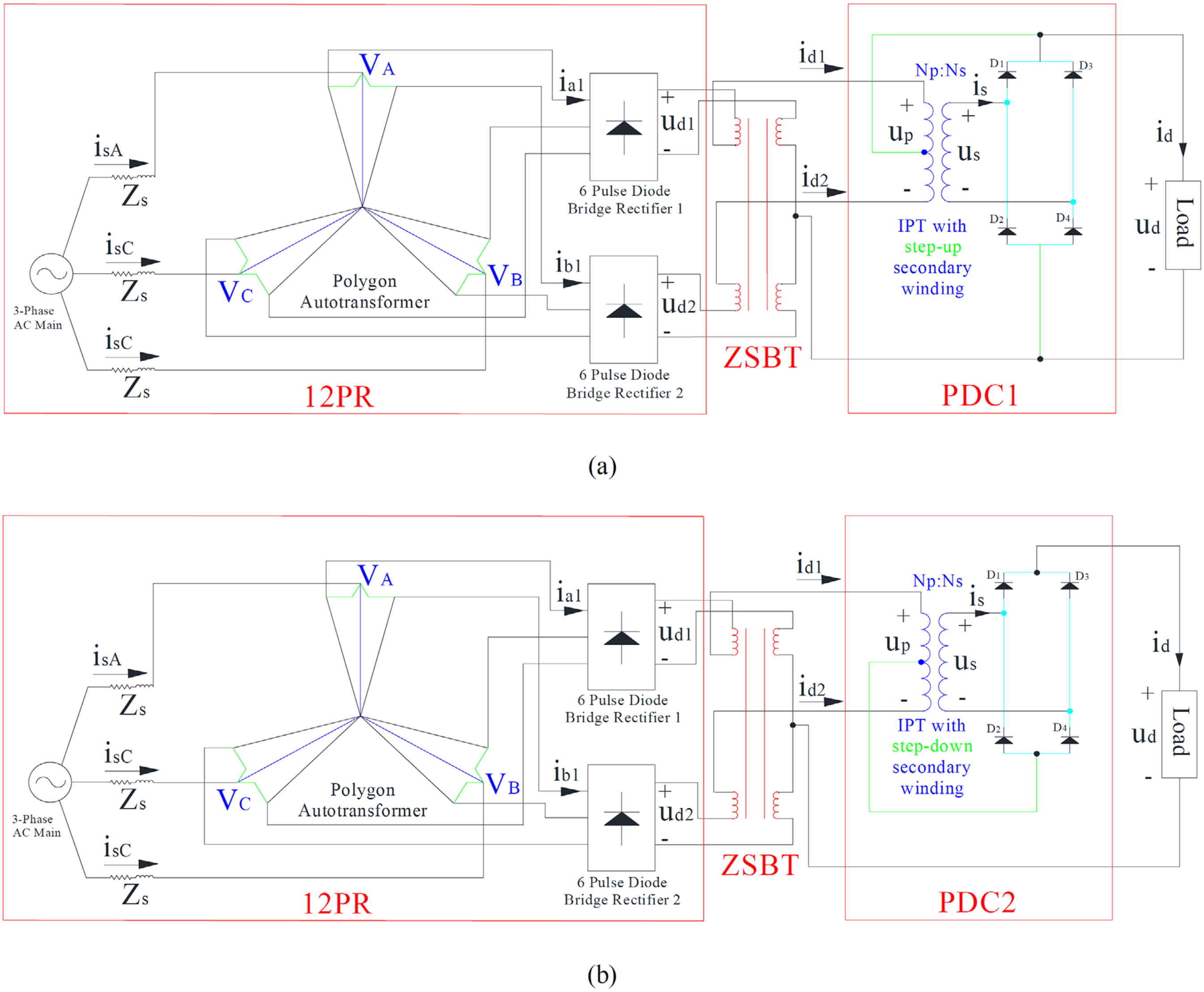

FIGURE 1 Connections of PDC at dc-link of 12PR rectifier, (a) PDC1 based on the step-up secondary winding and (b) PDC2 based on the step-down secondary winding

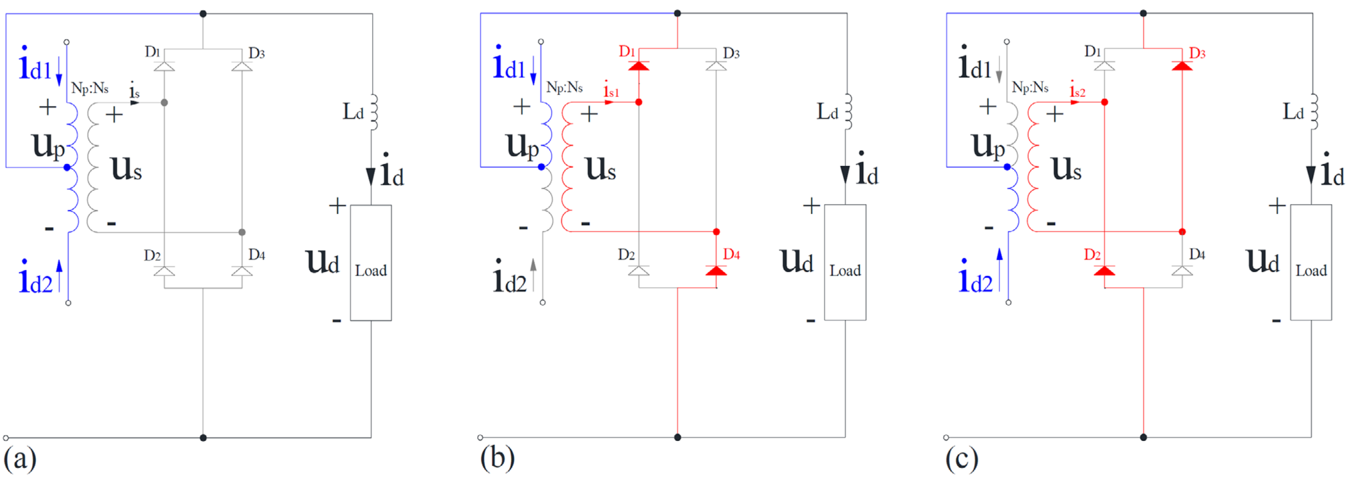

FIGURE 2 PDC1 operating modes, (a) Mode 1, (b) Mode 2 and (c) Mode 3

Mode 1: When the absolute value of u_s is less than u_d, the four diodes of the PDC1 are turned off and the current will be zero. The PDC1 will not work, and the MPR will act as a 12PR.

Mode 2: When u_s is larger than u_d, the diodes D_1 and D_4 turn on and the diodes D_2 and D_3 turn off. During this condition, the load voltage, i.e. u_d is greater than the voltage u_{d2}, which causes the current i_{d2} to be 0.

Mode 3: When $-u_s$ is larger than u_d, the diodes D_2 and D_3 turn on and the diodes D_1 and D_4 turn off. During this condition, the load voltage, i.e. u_d is greater than the voltage u_{d1}, which causes the current i_{d1} to be 0.

Similarly, regarding the operating modes of PDC2:

When $u_p > 0$, the diodes D_1 and D_4 turn off, and the diodes D_2 and D_3 turn on. During this condition, the input current of the PDC2 is positive ($i_s > 0$). When $u_p < 0$, the diodes D_1 and D_4 turn on, and the diodes D_2 and D_3 turn off. During this condition, the input current of the PDC2 is negative ($i_s < 0$).

In Figure 3, the voltages across the secondary and primary windings of the IPT are depicted. As can be seen in this figure, the IPT voltage frequency is 300 Hz, which is 6 times the supply frequency (50 Hz). This feature results in a reduction in the IPT size, weight, and volume. In PDC1, the minimum load voltage and primary winding voltage of the IPT circuit are considered to be 430.05 V (Figure 3a) and 30.55 V (Figure 3b), respectively. As a result, the turn ratio of the IPT is achieved, which is 14.17. As shown in Figures 3a and b, the functionality of the IPT with an additional secondary winding is the same as a step-up transformer with a turn ratio of 14.17. The main objective is that the proposed MPR should operate as a 24PR and the IPT must act as PDC1 with low current %THD. It should be noted that, unlike the existing published researches, the IPT used in the proposed design has an additional step-down secondary winding. The increase in voltage accommodated by the secondary winding results in a decrease in the current of the IPT on the secondary side and the PDC1 diodes. Therefore, the conduction losses are reduced and it is possible to use it for high current loads. In previous studies, it has been shown that the secondary to primary turn ratio must be 14.17 to have a minimum current %THD [22]. This is in good agreement with the proposed structure and the results presented in Figure 3.

The rating of the 24PR, which is based on the star autotransformer [22], was approximately 36.60% of the load power. But, the proposed 24PR, which is based on the polygon autotransformer in this paper, has a rating of 19.8% of the load rating, which is 16.8% less than the one given in [22]. Also, it can be used for retrofit applications, which is not possible for the one presented in [22]. From the design perspective, the proposed 24PR of this paper also benefits from a low-rating ratio (i.e. 28.92% of the load rating), which makes it a suitable candidate for use in retrofit applications.

Also, in [24], a pulse tripling circuit is provided to upgrade the 12PR to 36 pulses. It should be noted that the optimal turn ratio of the IPT used in the pulse tripling circuit [24] is 10.75, which is different from the optimal turn ratio of the IPT used in PDC1. Also, the connection method and the number of diodes in the pulse tripling circuit [24] are different from the PDC1. In general, the input current %THD in the 36PR [24] is less than the proposed 24PR based on PDC1, but has higher losses and costs.

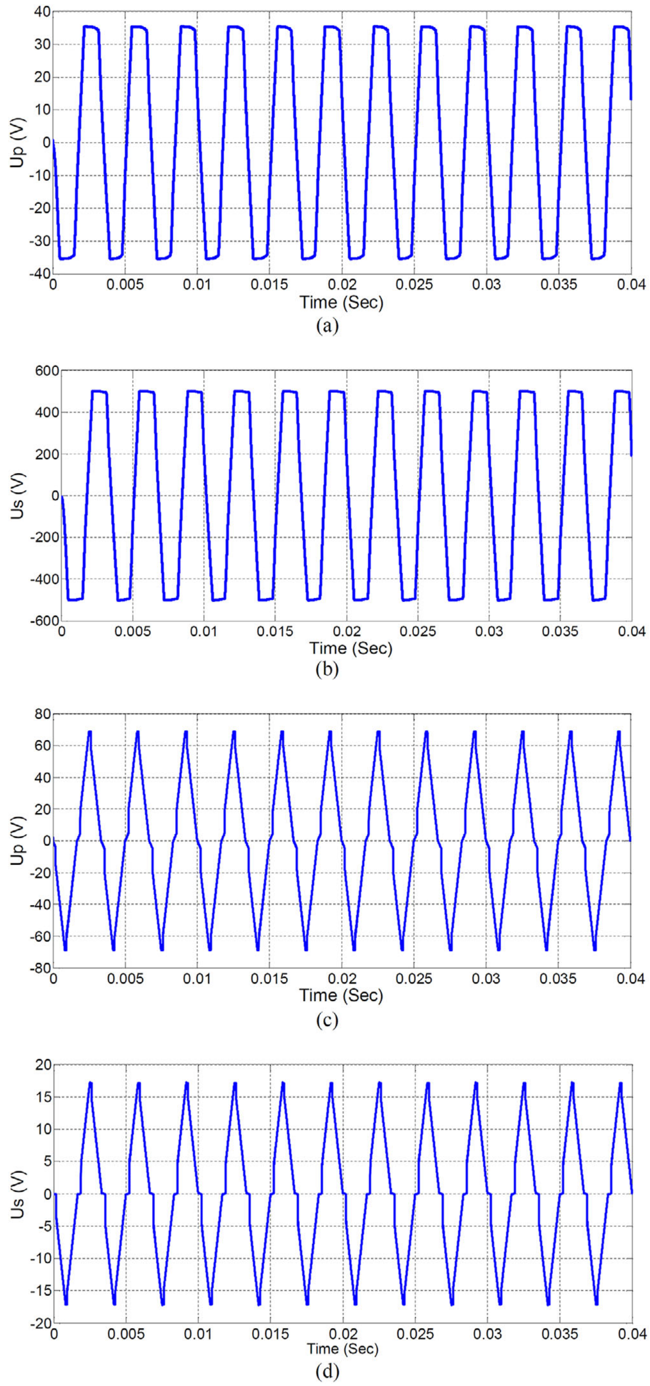

FIGURE 3 The voltage of IPT winding at 10 kW load, (a) Primary of the PDC1, (b) secondary of the PDC1, (a) Primary of the PDC2, (b) secondary of the PDC2

To achieve an input current %THD of less than 3%, following the requirements of the MIL-STD 1399 standard, another PDC based on IPT with a step-down secondary winding is presented, in this paper. The turn ratio of the PDC2 is equal to 0.25 and its connection method is different from PDC1 (shown in Figure 1b). The input and output voltage waveforms of the

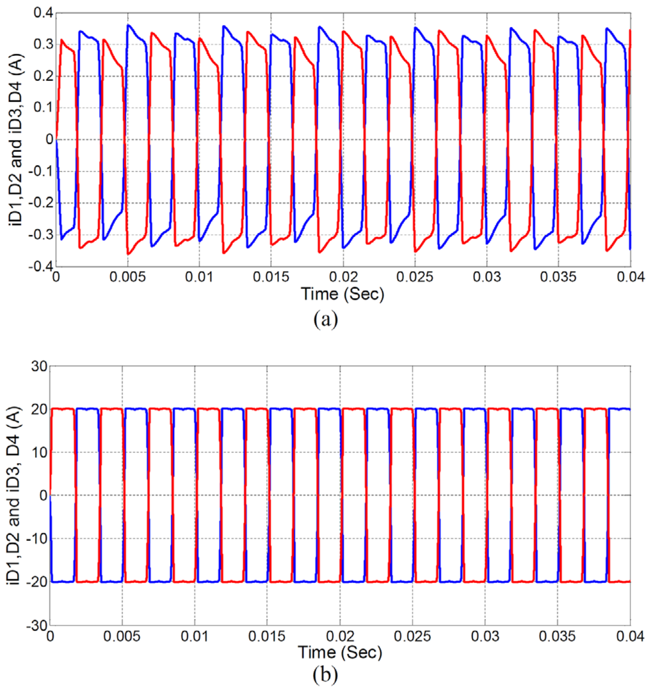

FIGURE 4 Diode currents of (a) PDC1 and (b) PDC2 at 10 kW load

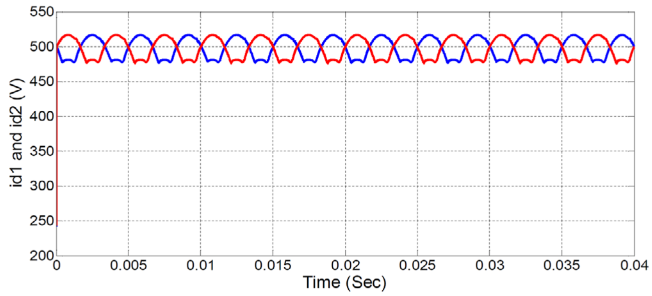

FIGURE 5 Output voltages of two 3-phase DBRs at 10 kW load

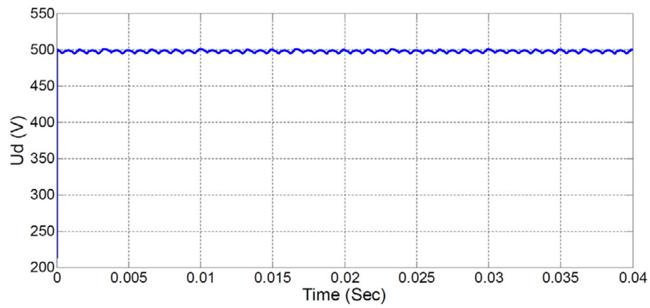

FIGURE 6 Load voltage of proposed 24PR at 10 kW load

PDC2 are shown in Figures 3c and d, respectively. In the PDC2, the primary and secondary winding voltage of the IPT circuit is considered to be 54.44 V and 11.34 V, respectively, with a turn ratio of 0.25 to achieve the lowest input current %THD in the proposed 24PR.

In Figure 4, the current of the diodes in PDC1 and PDC2 is depicted. In the PDC2, as with conventional rectifiers, the sum of the current through the diodes of the IPT with an additional step-down secondary winding is equal to the load current, and the diode conduction losses cannot be neglected under a heavy load current. In the PDC1, the circulating current is generated using an IPT with an additional step-up secondary winding and four diodes. This structure effectively leads to a reduction in harmonics. Also, this solution leads to a reduction in current through the secondary winding and the diodes of the PDC1. In other words, the main advantage of the PDC1 over the conventional one is the reduction of conduction losses, and the main advantage of the PDC2 over the conventional one is the reduction in input current %THD to less than 3%.

3 | DESIGNED AND SIMULATED 24PRS

The suggested 24PRs have been designed and simulated in a MATLAB environment. It is assumed that the resistive load is a 10 kW load and the input voltage is equal to 220 V. The simulation results are presented in Figures 5–8. The two DBRs output voltage is demonstrated in Figure 5. It is obvious that the retrofit polygon autotransformer is not isolated, therefore, ZSBT must be used. As it can be seen in Figure 5, the two three-phase DBRs independent operation is enabled by using the ZSBT. Also, the 24PR output voltage is presented in Figure 6. The output voltage ripple factor has been calculated for the proposed rectifiers in the range of 20%–100% of the load. The results show that for the light load (20% of the full load), the voltage ripple is 2.48%, 1.41% and 0.40% in the 24PR of [3], the 24PR with the PDC1 and the 24PR with the PDC2, respectively. Also, in the full load, the voltage ripple is 0.7%, 0.32% and 0.25% for the same 24PRs, respectively. It is obvious that the proposed 24PRs have a lower voltage ripple than the 24PR of [3].

According to Figure 7, the %THD of the input voltage is 2.78% and 1.73% in the suggested rectifier based on PDC1 and PDC2, respectively. Figure 8 presents the 24PR input line current with its spectrum in the case of using conventional PDC, PDC1, and PDC2. As seen in this figure, the 24PR based on the conventional PDC, reduces the %THD to 5.77%, which does not satisfy the IEEE 519 requirements. To achieve an acceptable range (5% according to the IEEE 519), a simple harmonic reduction method should be considered. In the suggested 24PR, which is based on the PDC1, the %THD is 3.67%. Also, to achieve an acceptable range (3% according to the MIL-STD 1399), another simple harmonic reduction method should be considered. In the suggested 24PR, which is based on the PDC2, the %THD is 1.45%. Compared with the input line current of the conventional 24PR, this is a significant improvement.

Power quality indices are compared in Table 1 between the conventional 24PR and the suggested 24PR based on PDC1 and PDC2. As listed in this table, the current %THD variations of the conventional 24PR are between 5.57% and 8.29% under full load and light load conditions, respectively. In other words, the IEEE-519 limits have not been satisfied. In the proposed 24PR based on PDC1, the input current %THD under full load and light load is 3.8% and 4.8% and its power factor is 0.993

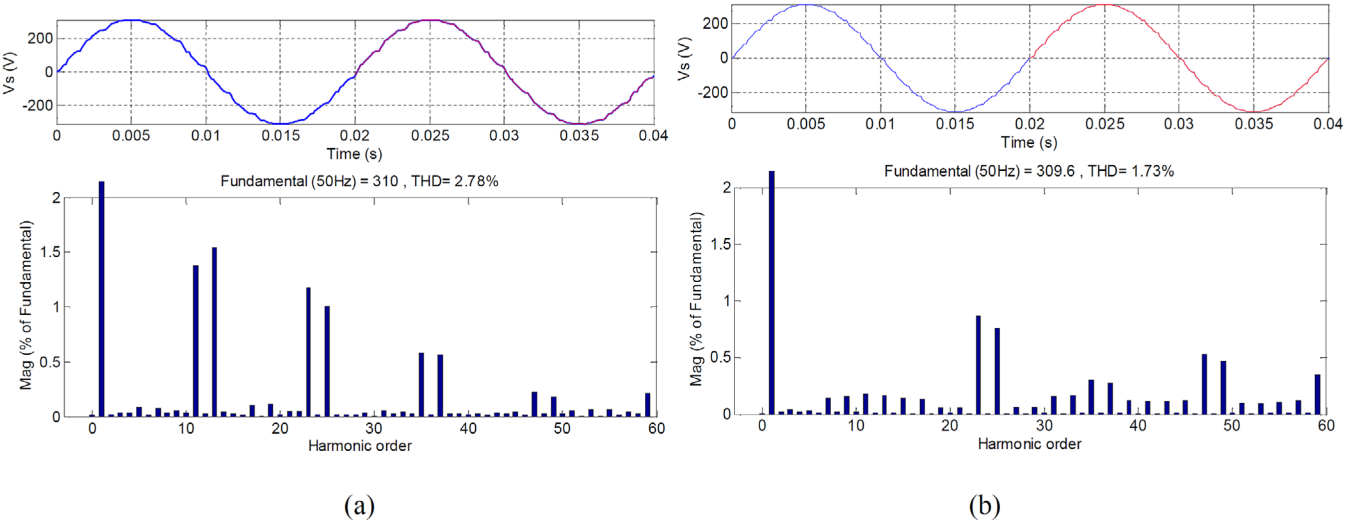

FIGURE 7 Input line voltage and its spectrum obtained for the 24-pulse rectifier (a) based on PDC1 and (b) based on PDC2 at 10 kW load

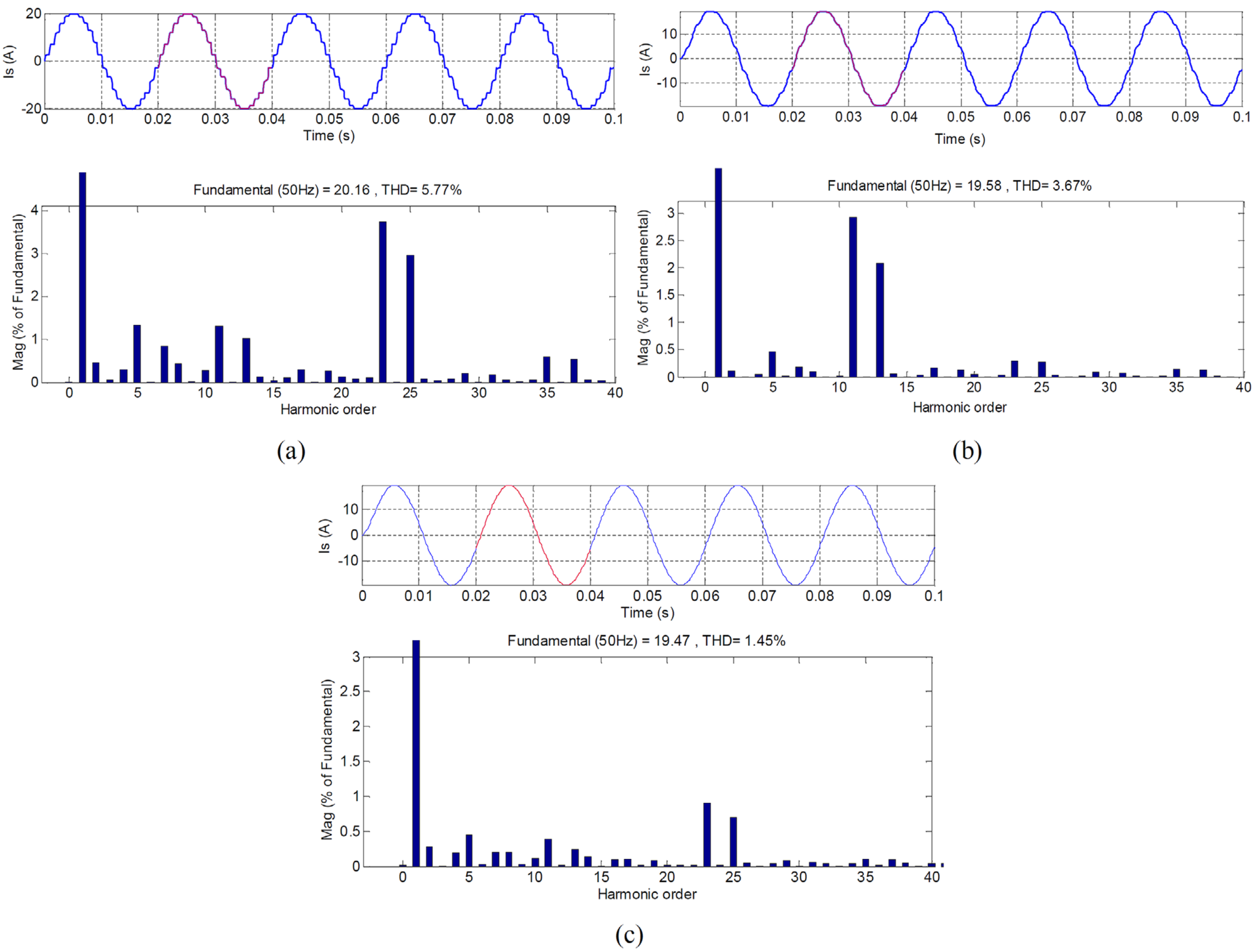

FIGURE 8 Simulated input line current and its spectrum of the 24PR based on the (a) conventional PDC, (b) PDC1, and (c) PDC2 at 10 kW load

TABLE 1 Comparison of simulated power quality parameters of the different MPRs

Sr. No.	Topology	% THD of V_{ac}	AC mains current I_{SA} (A)		% THD of I_{SA}, at		Distortion factor, DF		Displacement factor, DPF		Power factor, PF	
			Light load	Full load	Light load	Full load	Light load	Full load	Light load	Full load	Light load	Full load
1	6-pulse	5.64	4.90	20.10	52.53	28.53	0.885	0.959	0.985	0.988	0.873	0.948
2	Conventional 24PR	2.86	4.93	20.16	8.29	5.57	0.996	0.998	0.988	0.992	0.985	0.991
3	Proposed 24PR based on PDC1	2.78	4.85	19.58	4.82	3.67	0.999	0.999	0.999	0.999	0.987	0.993
4	Proposed 24PR based on PDC2	1.73	4.83	19.47	2.47	1.45	0.999	0.999	0.999	0.999	0.991	0.995

and 0.987, respectively. Also, in the proposed 24PR based on PDC2, the input current %THD under full load and light load is 1.45% and 2.47% and its power factor is 0.995 and 0.981, respectively.

For more electric aircraft applications, the operating frequencies can be 400 or 800 Hz. At these frequencies, the line current and the current spectrum are indicated in Figures 9 and 10. The current %THD is less than 3% in the range of 400 Hz (Figure 9) to 800 Hz (Figure 10), which assures agreement with DO-160G limits [8], and according to the obtained results, the proposed 24PRs can be used in aircraft applications.

4 | EXPERIMENTAL TEST RESULTS

Figure 11 demonstrates the prototype of the proposed 24PR connected to a 10-kW load. The experimental results are presented in Figures 12 and 13.

Comparing the simulation and test results, it is obvious that the model of the suggested 24PR has very good accuracy. The test results under the full load condition presented in Figure 12a demonstrate that the %THD of the input line current of the 24PR based on PDC1 and PDC2 is 3.8% and 1.7%, respectively. Figures 12b and c indicate the same parameters under partial loading condition. It can be seen in this figure that the %THD of the 24PR based on PDC1 is 4.8% and 4.2% and the %THD of the 24PR based on PDC2 is 2.5% and 2.1% under 20% and 50% of the full load, respectively. The light load %THD, i.e. under 20% of the full load, has a small growth compared to the full load %THD and it remains below 5% for 24PR based on PDC1 and it remains below 3% for 24PR based on PDC2. These experimental results verify that the harmonics are considerably reduced and the proposed 24PR based on PDC1 %THD is less than 5%, which meets the IEEE-519 and the proposed 24PR based on PDC2 %THD is less than 3%, which meets the MIL-STD 1399 requirements.

According to Figure 13, the %THD of the input line and phase voltage is 1.7% in the suggested rectifier based on PDCs. The load voltage and current are presented in Figure 14. According to Figure 14, after using the PDCs, the measurement results show the proposed rectifier operates as a 24-pulse rectifier. However, because of the filtering of inductance, the load voltage and load current are smothered in the experimental results.

5 | APPARENT POWER RATINGS

The proposed polygon autotransformer (T_{AB}, T_{BC}, and T_{CA}), ZSBT, and IPT ratings are calculated for the suggested 24PR using the following equation, which is based on the theoretical calculations presented in [2]:

$$s = 0.5 \sum V_{winding} I_{winding} \tag{1}$$

In this equation, $I_{winding}$ is the winding full load current and $V_{winding}$ presents the rms voltage of the winding. These parameters, given in Table 2, are determined by using a 10 kVA load. It can be seen that the retrofit polygon autotransformer, ZSBT, step-up IPT, and step-down IPT ratings are 1.98 kVA, 0.652 kVA, 0.259 kVA, and 0.305 kVA, respectively. The rating of the step-down IPT is 0.46% higher than that of the step-down IPT. Therefore, it can be said that the magnetic parts rating of the suggested 24PR based on PDC1 and PDC2 is 28.9% and 29.3% of the load power, respectively.

Since the IPT has a secondary winding in the proposed method, the rating of the PDCs is slightly higher than the conventional PDC. But the rating of the ZSBT used in the proposed PDCs is slightly less than the ZSBT employed in the conventional PDC. In the PDC1, the volt-ampere rating of the IPT and ZSBT is about 6.52% and 2.59% of the load power, respectively.

In the conventional PDC, these values are about 7.5% and 1.65% of the load power. However, the main advantage of the proposed 24PRs is that the current %THD is lower than the conventional 24PR, and the application of the used PDC1 and PDC2 has reduced the current %THD to 3.67% and 1.45%, respectively, which is a good solution for more electric aircraft.

Figure 15 compares the two proposed 24PR kVA ratings with those of other MPRs. The kVA rating of the proposed 24PR based on PDC1 and PDC2 is 28.9% and 29.3% of the load power, respectively. In this figure, it can also be observed that the 24PRs proposed in references [12] and [13] have a higher rating than the suggested one. Moreover, the proposed

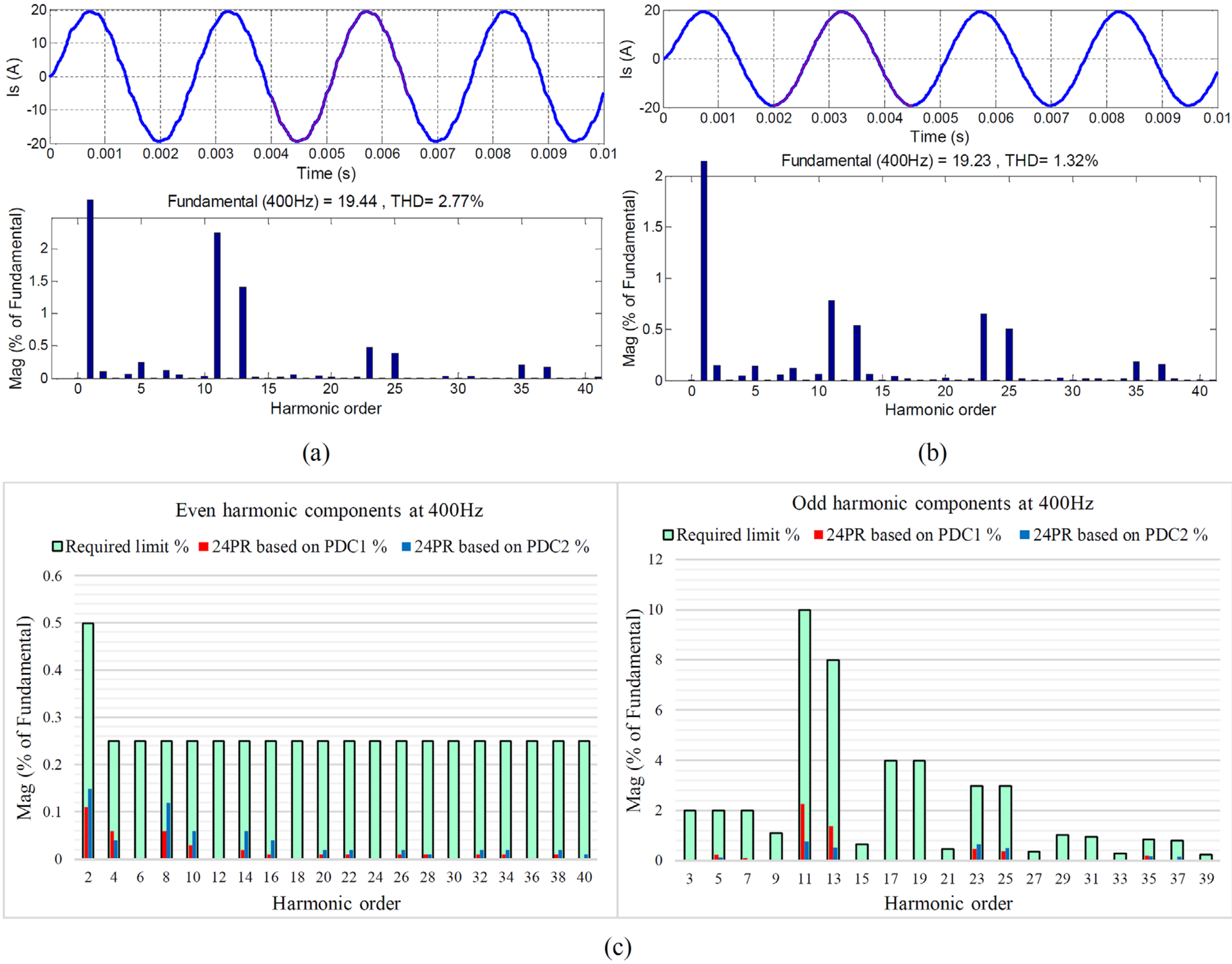

FIGURE 9 Simulated line current and its spectrum of the proposed 24PR at 400 Hz (a) based on PDC1, (b) based on PDC2 and (c) even/odd current harmonics at 400 Hz

TABLE 2 Windings RMS voltage and current for different transformers and their VA rating for 10 kW load

Transformer	RMS values	W_1	W_2	W_3	W_4	W_5	Rating (VA)
T_{AB}	V_{rms} (V)	17.92	17.92	45.6	45.6	379.6	660.34
	I_{rms} (A)	5.61	5.62	5.61	5.62	1.6	
T_{BC}	V_{rms} (V)	17.92	17.92	45.6	45.6	379.6	660.34
	I_{rms} (A)	5.61	5.62	5.61	5.62	1.6	
T_{CA}	V_{rms} (V)	17.92	17.92	45.6	45.6	379.6	660.34
	I_{rms} (A)	5.61	5.62	5.61	5.62	1.6	
ZSBT	V_{rms} (V)	30.35	30.35	30.35	30.35		652.52
	I_{rms} (A)	10.75	10.75	10.75	10.75		
IPT with a step-up secondary winding	V_{rms} (V)	30.35	430.05				259.89
	I_{rms} (A)	10.75	0.45				
IPT with a step-down secondary winding	V_{rms} (V)	45.44	11.34				305.37
	I_{rms} (A)	*9.74*	*14.83*				

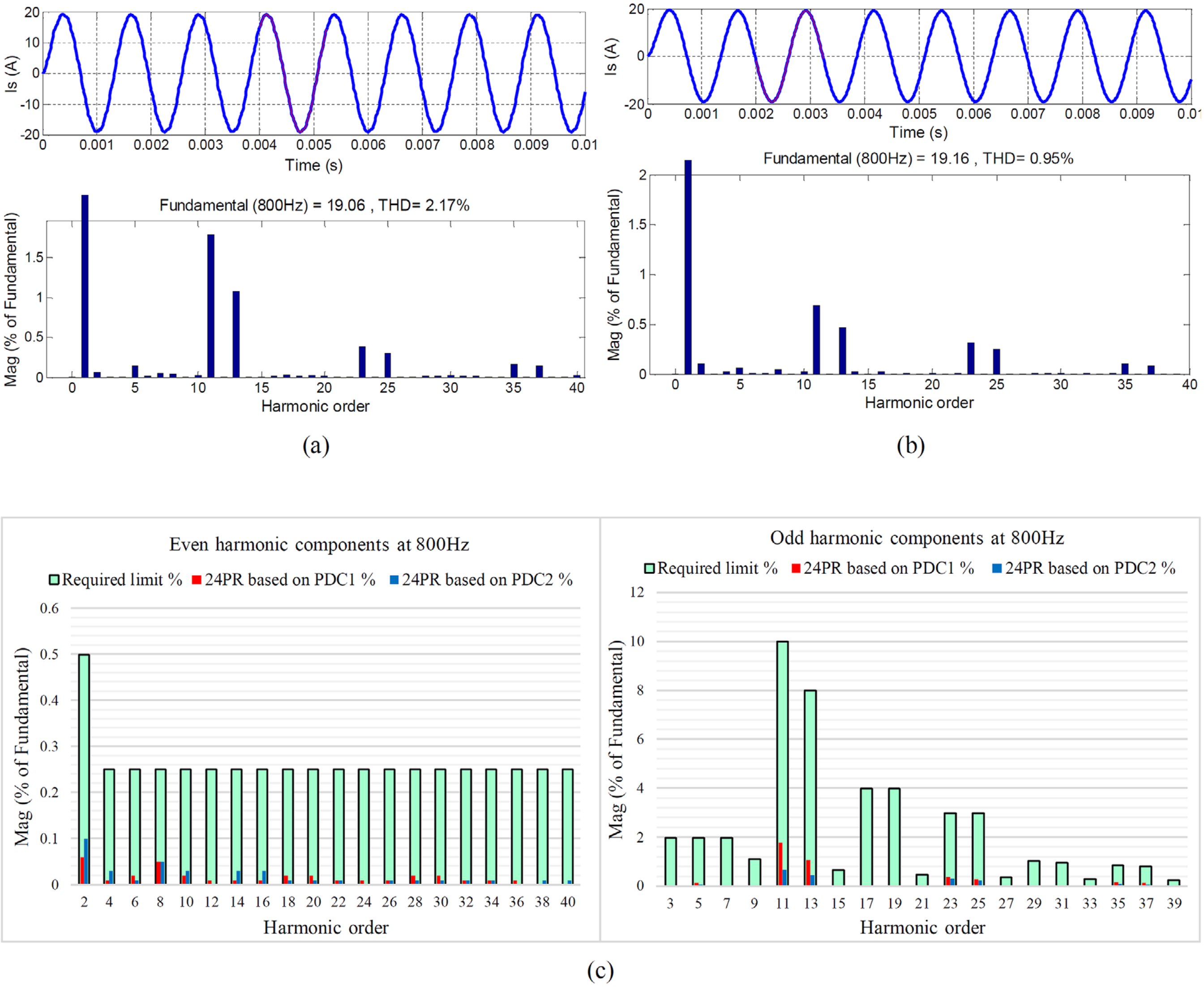

FIGURE 10 Simulated line current and its spectrum of the proposed 24PR at 800 Hz (a) based on PDC1, (b) based on PDC2 and (c) even/odd current harmonics at 800 Hz

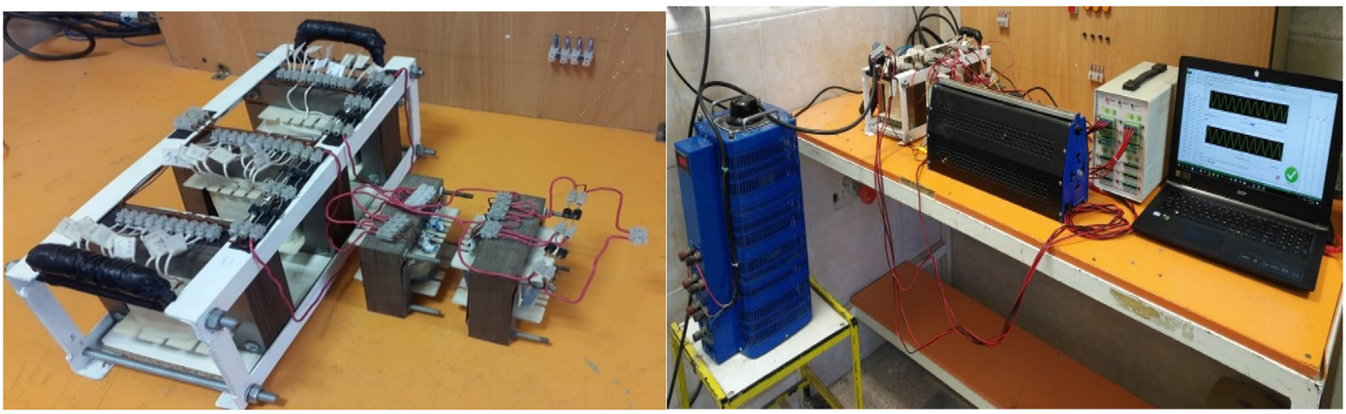

FIGURE 11 A laboratory prototype of proposed 24PR

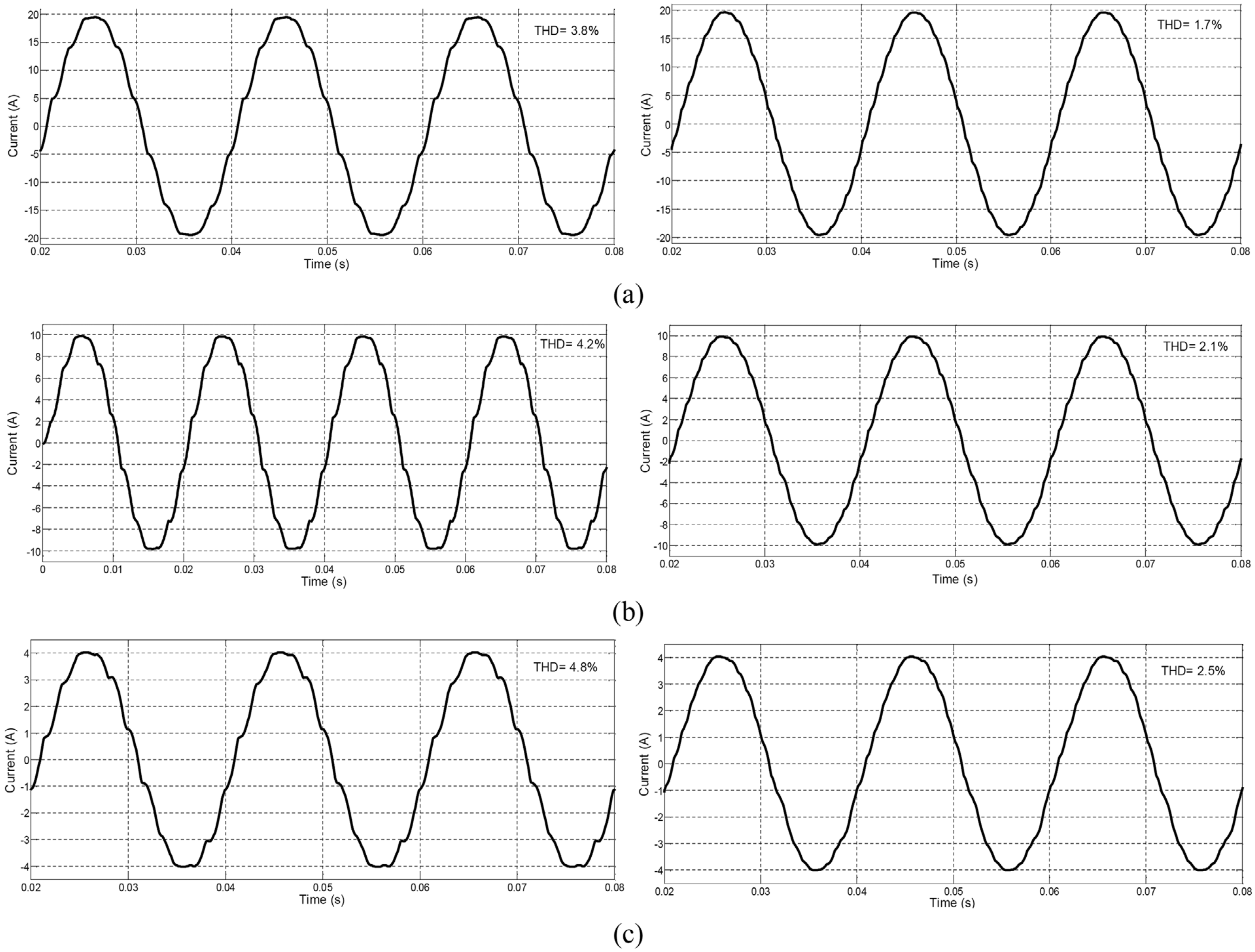

FIGURE 12 Measurement of input line current and its %THD of the 24PR based on PDC1 and PDC2, respectively, under (a) 100%, (b) 50%, and (c) 20% of full load (10 kW load)

rectifier based on PDC1 rating is 10.81%, 5.08%, 11.35%, 16.55%, 1.20%, 35.06%, 28.34%, 19.35%, 15.41% and 14.69% less than that of other MPRs in [5, 9–11, 14–18, 20].

It must be said that the total cost and size can be specified by the transformer magnetic ratings. Also, in [17] and [18], it has been mentioned that the cost can be estimated by the transformer rating. Therefore, the suggested rectifier has a lower rating, weight, volume, and cost. In other words, the suggested 24PRs provide a techno-economic solution for more electric aircraft and also other industrial applications, and it has similar performance compared to rectifiers with higher pulse numbers, and it has also a lower number of used components and less complexity in design.

The power losses of diodes are determined by considering the voltage drop of the diode (V_f= 0.7 V), the diode internal resistance (R_d = 1 mΩ), and the diode current I_d, as follows:

$$P_{Diode} = \frac{1}{\pi}\int_{0}^{\pi}(V_f I_d + I_d^2 R_d)dt \ = V_f \ I_d + I_d^2 R_d \qquad (2)$$

The iron and winding losses are calculated as follows:

$$P_{core} = m_c \ k_c B_m^{\alpha} f_T^{\beta} \qquad (3)$$

where the parameters have been given in [28]. The copper losses can be determined using the following equation using the parameters defined in [28]:

$$P_{copper} = \sum J\rho_{cu} \ (MLT_i)\, K_i N_i I_i \qquad (4)$$

where, MLT_i is defined as the mean length per turn for the ith winding, K_i is AC/DC resistance factor, N_i and I_i are the turns and RMS current of the ith winding, respectively. The efficiency of the suggested 24PRs has been calculated based on simulations and using the parameters listed in Table 3 and Equations (2)–(4). The total losses of the proposed 24PR based on PDC1 and PDC2 are 222.1 W and 275.2 W, respectively. Therefore, their efficiency will be 97.82% and 97.32%, respectively.

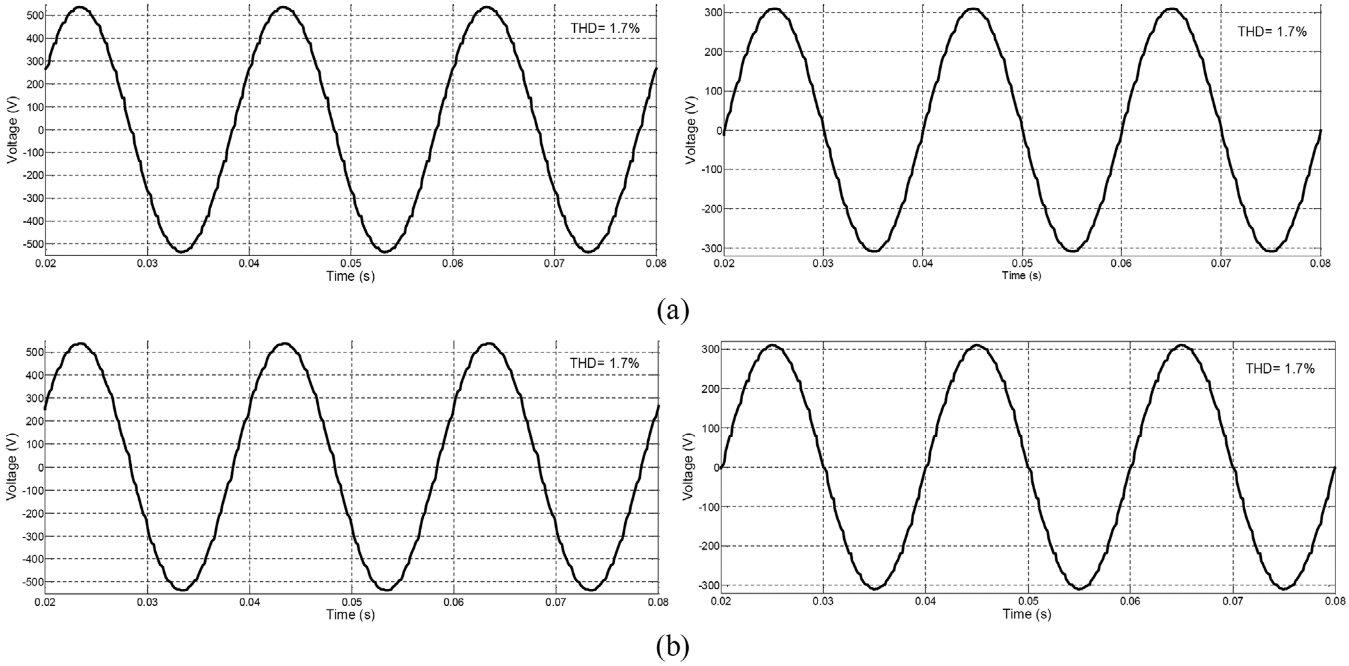

FIGURE 13 Measurement of input line voltage and phase voltage and its %THD of the 24PR based on (a) PDC1 and (b) PDC2

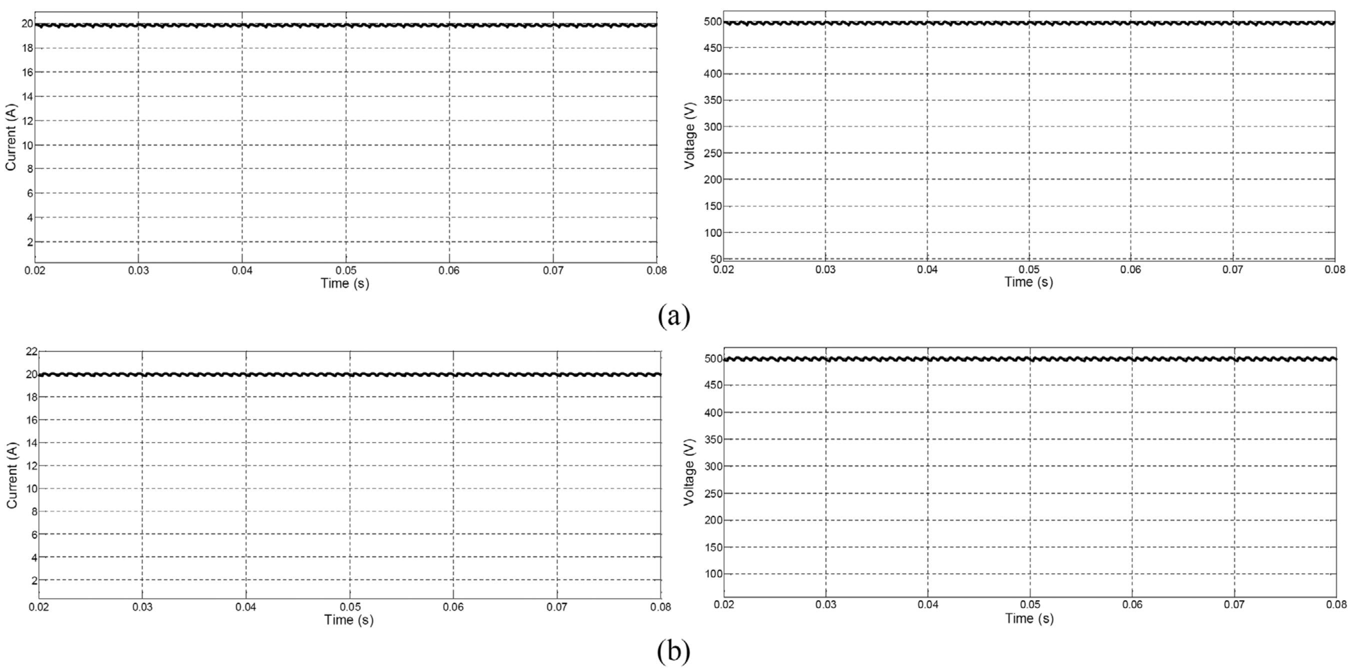

FIGURE 14 Measurement of load voltage and load current of the proposed 24PR based on (a) PDC1 and (b) PDC2

Also, the 24PR volume can be estimated, as follows [28]:

$$V_T = K_{vol}\, A_P^{0.75} = K_{vol}\left(\frac{S_T}{k_f k_u B_m J f_T}\right)^{0.75} \tag{5}$$

where, K_{vol} is a constant related to core configuration, whose value is 19.7 in the case of laminations, k_f is a waveform coefficient, k_u denotes window utilization factor, B_m is the maximum flux density in tesla, f_T represents frequency of operation, and J is current density. Using the parameters listed in Table 3, and by using Equation (5), the volume of the proposed rectifier based on PDC1 and PDC2 is 1931 cm^3 and 1951 cm^3, respectively. Therefore, their power to volume ratio will be 5.18 W/cm^3 and 5.13 W/cm^3, respectively.

The proposed 24PR configurations are compared with 20PR [9–11, 29], 24PR [22], 40PR [15, 16], and 72PR [17, 18] in

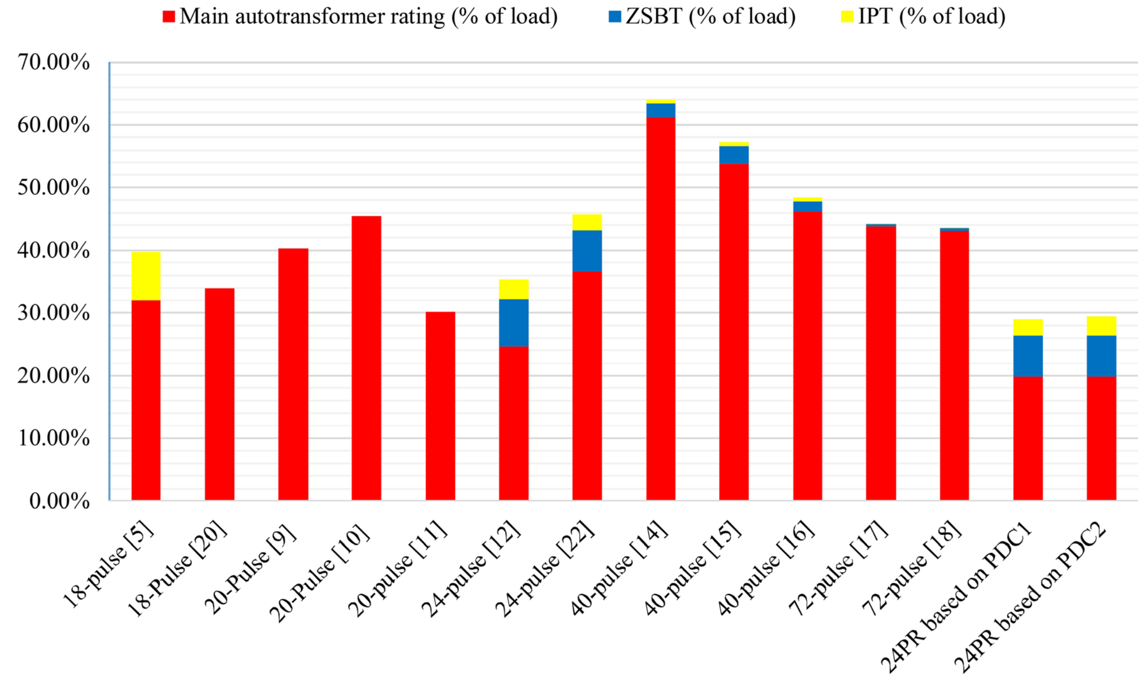

FIGURE 15 Comparison of kVA ratings in different MPRs

TABLE 3 Parameters for losses calculation

Symbol	Parameter	Value
B_m	Maximum flux density	1.2 T
K_f	Waveform coefficient	4.44
K_u	Window utilization factor	0.4
ρ_{cu}	Electrical resistivity of Cu	2.3×10^{-8} Ωm
J	Current density	2.3 A/mm^2
k_c	Material coefficient	6.754×10^{-4}
α	Exponent of flux density	1.559
β	Exponent of frequency	1.651
K_i	AC/DC resistance factor	1.05

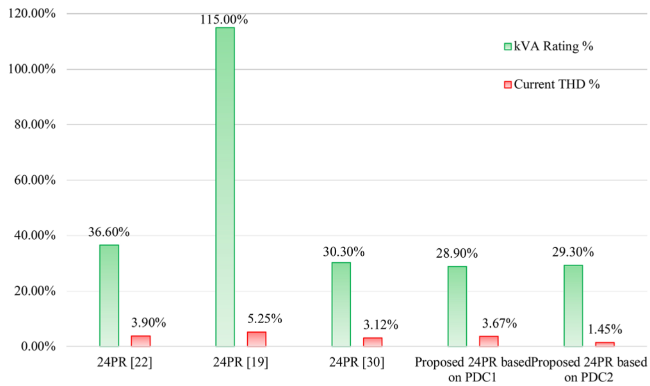

FIGURE 16 Comparative evaluation of kVA and %THD of proposed 24PRs with existing 24PRs

Table 4 in terms of %THD, efficiency, the number of diodes, magnetic rating, and cost. According to the procedure mentioned in [17, 18, 29], the cost can be estimated at 4.5 times of kVA rating of a transformer. Also, it should be emphasized that the total cost and size of the system are determined by the transformer magnetic rating. As can be seen in Table 4, one can easily conclude that there is a direct relationship between the number of pulses and the number of components, the kVA rating, and finally the cost. As an example, the cost of the 24PR proposed in [22] is about 241.69$, while the total cost of the proposed system is about 166.05$, which is lower than the existing rectifiers. Considering this table, it can be said that the proposed 24PR based on PDC1 and PDC2 can provide effective performance similar to a higher pulse system and has lower components, less complexity in terms of design, and finally provides an economical solution for industrial applications. Also, the proposed rectifier based on PDC1 and PDC2 has an efficiency of 97.82% and 97.32%, respectively, which is a higher efficiency compared to other MPRs.

In Figure 16, the kVA rating and current %THD of the suggested 24PRs are compared with the rating and current %THD of existing 24PRs. It is obvious that the suggested 24PR based on PDC1 and PDC2 topology rating is 28.90% and 29.38, respectively, which is lower than the kVA rating of existing 24PRs. Also, its current %THD of the 24PR based on PDC1 is less than 5% and similar to the current %THD in 24PRs, but its current %THD of the 24PR based on PDC2 is less than 3% and lower than the current %THD in 24PRs. In this figure, it can be observed that the proposed rectifier based on PDC1 rating is 7.7%, 86.1%, and 1.4% less than that of [22, 19, 30] 24PRs, respectively. As mentioned before, it can be said that the

TABLE 4 Cost and size comparison of proposed 24PR with existing MPRs

Part	Unit cost ($)	20-Pulse [9]	20-Pulse [10]	20-pulse [11]	20-Pulse [29]	24-pulse [22]	24-pulse [19]	40-pulse [14]	40-pulse [15]	40-pulse [16]	72-pulse [17]	72-pulse [18]	Proposed 24PR based on PDC1	Proposed 24PR based on PDC2
% of THD		3.04	3.70	3.70	3.71	3.9	5.25	2.55	2.22	2.65	1.68	2.19	3.67	1.45
% of Efficiency		97.65	94.43	97.73	97.75	97.26	96	97.54	97.48	97.50	97.53	97.40	97.82	97.32
Total kVA rating of the autotransformer (% of load rating)	4.5 times the kVA	40.27	45.47	30.12	44.48	45.71	115.00	63.98	57.26	48.45	44.33	43.61	28.9	29.38
Diode	2.25	20	20	20	20	16	14	42	42	42	38	38	16	16
Approximate total cost ($)		226.2	249.6	180.5	245.2	241.69	549.69	382.4	352.2	312.5	285	281.7	166.05	170.23

total cost and size can be specified by the transformer magnetic rating. It should be noted that the 24PR given in [30], is based on a zigzag autotransformer and the ZSBT is not used in its structure, so the circuit impedance mismatches, transformer winding rounding errors, supply voltage unbalance, and harmonic distortions, can have a very negative effect on the performance of this rectifier [2]. Therefore, the suggested rectifier has a lower rating, weight, volume, and cost. In other words, the suggested 24PRs provide a techno-economic solution for industrial applications.

6 | CONCLUSION

In this paper, two cost-effective 24PRs were proposed based on a retrofit polygon autotransformer and two PDCs. The PDC1 was based on an IPT, which had an additional step-up secondary winding and four diodes connected to the dc side of the rectifier. The currents in the secondary winding of the IPT and the four diodes of the PDC1 were very low. Consequently, the conduction losses of the PDC1 were negligible, which in turn made it suitable for high power loads. The PDC2 was based on an IPT, which had an additional step-down secondary winding and four diodes connected to the dc side of the rectifier. In comparison with the conventional 24PR, the %THD of the input line current of the proposed 24PR based on PDC1 and PDC2 was remarkably decreased to be less than 5% and 3% at 50 Hz, which satisfied the IEEE 519 and MIL-STD 1399. The input current %THD of the proposed 24PRs was less than 3% at 400 and 800 Hz, which satisfied DO-160G requirements and made it suitable for application in more electric aircraft. Also, in comparison with the conventional 24PR, it was shown that the rating of the proposed 24PRs could be decreased to almost 29% of the load power, which is important for more electric aircraft.

ORCID

R. Abdollahi https://orcid.org/0000-0003-2680-3445
G. B. Gharehpetian https://orcid.org/0000-0003-1521-790X
A. Anvari-Moghaddam https://orcid.org/0000-0002-5505-3252
F. Blaabjerg https://orcid.org/0000-0001-8311-7412

REFERENCES

1. Singh, B., et al.: Multi-pulse AC-DC converters for improving power quality: A review. IEEE Trans. Power Electron. 23(1), 260–281 (2008)
2. Paice, D.A.: Power Electronic Converter Harmonic Multipulse Methods for Clean Power. IEEE Press New York (1996)
3. Garg, V., et al.: 24-pulse AC–DC converter for harmonic mitigation. IET Power Electron. 2(4), 364–374 (2009)
4. Villablanca, M.E., et al.: Harmonic improvement in 12-pulse series-connected line-commutated rectifiers. IET Power Electron. 2(4), 466–473 (2009)
5. Singh, B., et al.: Autoconnected transformer-based 18-pulse AC–DC converter for power quality improvement in switched mode power supplies. IET Power Electron. 3(4), 525–541 (2010)
6. IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems. In: IEEE Std 519-2014, IEEE, 11 June 2014
7. IEC Standard 61000-3-2:2004, Limits for Harmonic Current Emissions, International Electromechanical Commission. Geneva (2004)

8. RTCA Inc.: Environmental Conditions and Test Procedures for Airborne Equipment – RTCA DO-160. RTCA Inc. Std. http://www.rtca.org
9. Kalpana, S.P.P.R., et al.: A 20-pulse asymmetric multi-phase staggering autoconfigured transformer for power quality improvement. IEEE Trans. Power Electron. 33(2), 917–925 (2018)
10. Kalpana, R., et al.: Autoconnected-transformer-based 20-pulse AC–DC converter for telecommunication power supply. IEEE Trans. Ind. Electron. 60, 4178–4190 (2013)
11. Prakash, P.S., et al.: Inclusive design and development of front-end multi-phase rectifier with reduced magnetic rating and improved efficiency. IEEE J. Emerg. Sel. Top. Power Electron. 8(3), 2989-3000 (2019). https://doi.org/10.1109/JESTPE.2019.2949138
12. Meng, F., et al.: Load adaptability of active harmonic reduction for 12-pulse diode bridge rectifier with active interphase reactor. IEEE Trans. Power Electron. 30(12), 7170–7179 (2015)
13. Izadinia, R., Karshenas, H.R.: Current shaping in a hybrid 12-pulse rectifier using a Vienna rectifier. IEEE Trans. Power Electron. 33(2), 1135–1142 (2018)
14. Abdollahi, R., Gharehpetian, G.B.: Inclusive design and implementation of Novel 40-Pulse AC-DC converter for retrofit application and harmonic mitigation. IEEE Trans. Ind. Electron. 63(2), 667–677 (2016)
15. Singh, B., Gairola, S.: A 40-Pulse AC-DC converter fed vector-controlled induction motor drive. IEEE Trans. Energy Conver. 23, 403–411 (2008)
16. Abdollahi, R.: A simple harmonic reduction method in 20-pulse AC-DC converter. J. Circuits, Syst., Comput. 28(1), 1950013 (2019)
17. Abdollahi, R., Gharehpetian, G.B., Mahdavi, M.S.: Cost-effective multi-pulse AC-DC converter with lower than 3% current %THD. Int. J. Circuit Theory Appl. 47(7), 1105–1120 (2019)
18. Abdollahi, R.: Power quality enhancement of a T-connected autotransformer based on 72-pulse AC–DC converter with rated power reduction. Electr. Eng., 102 1253—1264 (2020). https://doi.org/10.1007/s00202-020-00948-1
19. Yang, S., et al.: A novel 24-pulse diode rectifier with an auxiliary single-phase full-wave rectifier at DC side. IEEE Trans. Power Electron. 32(3), 1885–1893 (2017)
20. Chen, J.: Investigation on the selection and design of step-up/down 18-pulse ATRUs for more electric aircrafts. IEEE Trans. Transp. Electrif. 5(3), 795-811 (2019). https://doi.org/10.1109/TTE.2019.2930422
21. Chen, J., et al.: Evaluation on the autoconfigured multipulse AC/DC rectifiers and their application in more electric aircrafts. IEEE Trans. Transp. Electrific. 6(4), 1721–1739 (2020)
22. Meng, F., et al.: A simple harmonic reduction method in multi-pulse rectifier using passive devices. IEEE Trans. Ind. Inf. 13(5), 2680–2692 (2017)
23. Meng, F., et al.: Dual passive harmonic reduction at DC link of the double-star uncontrolled rectifier. IEEE Trans. Ind. Electron. 66(4), 3303–3309 (2019)
24. Gao, L., et al.: A 36-pulse diode-bridge rectifier using dual passive harmonic reduction methods at DC link. IEEE Trans. Power Electron. 34(2), 1216–1226 (2019)
25. Wang, J., et al.: Harmonic reduction for 12-pulse rectifier using two auxiliary single-phase full-wave rectifiers. IEEE Trans. Power Electron. 35(12), 12617–12622 (2020)
26. Wang, J., et al.: A simple 36-pulse diode rectifier with hybrid pulse multiplication inter-phase reactor at DC side. IEEE Trans. Emerg. Sel. Top. Power Electron. 9(3), 3540-3555 (2021) https://doi.org/10.1109/JESTPE.2020.3017525
27. Du, Q., et al.: Harmonic reduction methods at DC side of parallel-connected multi-pulse rectifiers: A review. IEEE Trans. Power Electron. 36(3), 2768–2782 (2021)
28. McLyman, C.W.T.: Transformer and Inductor Design Handbook. Taylor & Francis, London, pp. 5–7, (2011)
29. Abdollahi, R., Gharehpetian, G.B.: A 20-pulse autotransformer rectifier unit for more electric aircrafts. IEEE J. Emerg. Sel. Top. Power Electron. 9(3), 2992–2999 (2021). https://doi.org/10.1109/JESTPE.2020.2990670
30. Kalpana, R., et al.: Power quality enhancement using current injection technique in a zigzag configured autotransformer based 12-pulse rectifier. IEEE Trans. Ind. 54(5), 5267–5277 (2018)

How to cite this article: Abdollahi R., et al.: An improved 24-pulse rectifier for harmonic mitigation in more electric aircraft. IET Power Electron. 2021; 1–14. https://doi.org/10.1049/pel2.12168.