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Auxiliary Pulse Tripling Circuit with Low kVA Rating to Reduce Input Current Harmonic Distortion in 12-pulse Rectifier

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ABSTRACT

In recent years, to increase the number of pulses in 12-pulse autotransformer rectifiers (12-PARs) and reduce the input current total harmonic distortion (IC-THD) without increasing the cost and complexity, the pulse multiplication circuit technique has been proposed. With this approach, to upgrade the rectifier structure from 12 to 36 pulses, an auxiliary pulse tripling circuit (APTC) with a very small kilovolt ampere rate (a kilovolt ampere equal to 1.34% of the rated load power) is presented. The proposed APTC consists of an unconventional interphase transformer (UIPT) with two diodes in the primary winding and a single-phase diode bridge rectifier connected to the secondary winding. In addition, the 12-phase autotransformer used in the proposed structure is based on a polygon connection with a very low kilovolt-ampere rate.

I. Introduction

With the development of power electronic converters, most DC drives have been replaced by variable frequency induction motor drives [1]. Induction motor drives are widely used in industrial applications. The 6-pulse diode bridge rectifier used in variable frequency induction motor drives causes problems such as power factor reduction and harmonic injection into the main line current due to the locking process. These current harmonics distort the voltage waveform by passing through the impedance of the source. Harmonics generally cause many problems in the power system, equipment, electrical loads, and especially measuring and control devices. Standards such as IEEE-519 and IEC61000-3-2 were developed to reduce the main current harmonics and limit current and voltage disturbances. To reduce harmonics, two methods of using filters and multi-pulse converters have been suggested [2]. Power quality can be improved by using active and passive filters; however, the use of passive filters has problems such as high losses, large required space, and the dependence of efficiency on frequency changes. Active filters also have problems such as complexity and high cost. Therefore, the method of increasing the number of pulses in the converter can be proposed and used as an efficient method for improving the power quality indicators, reducing the current passing through the power electronics, and reducing the kilovolt-ampere rate of the transformer. In recent years, multi-pulse rectifiers due to low harmonic distortion, low output voltage ripple, simple configuration, strong robustness, and correction of inherent power factor have been successfully used to improve power quality indicators in industrial applications [3]. To reduce line current harmonics, various designs of 12- and 18-pulse rectifiers have been reported in [4-6], but in these designs, the current harmonic reduction is more than 5%. To improve the power quality indicators, increasing the number of output phases of the phase shift transformer is the main solution. However, rectifiers with more pulses require a transformer with more size and volume, which increases the KVA rating and the total cost of multi-pulse rectifiers. [7-10 and 33].

The 40-pulse rectifier [9] includes a 20-pulse rectifier based on a 10-phase autotransformer and a circuit to upgrade the 20-pulse rectifier to 40-pulse. Note that the structure of the 10-phase autotransformer is very complex, and the kVA rating of the 40-pulse rectifier is very high and is equivalent to 64% of the nominal load. As a result, in industrial applications, 12-pulse rectifiers are mainly used because of the lightness and simplicity of the transformer, and as a result, the kilovolt-ampere rate and low cost. However, the total harmonic distortion of the input current in conventional 12-pulse rectifiers is theoretically approximately 15%, and without filtering, they cannot meet the requirements of the IEEE-519 standard. To reduce the harmonics and meet the requirements of the standards by reducing the weight, dimensions, and kilovolt-ampere rate of the multi-pulse rectifier, several methods based on active or passive auxiliary circuits in 12-pulse rectifiers have been reported in [11-13].

To reduce the harmonics in [14-21], several active auxiliary circuits are present in the DC link of the rectifier. In [14], an active interphase reactor with an auxiliary circuit, in [15] a DC-side current injection circuit, and in [16-17] an active interphase reactor is used to reduce harmonics. In [18, 19], the active interphase reactor along with an additional secondary winding is connected to an auxiliary modulation circuit, which leads to increased complexity, loss, and overall cost. The use of an active power filter [20] and a Vienna rectifier [21] can also increase the power quality of multi-pulse rectifiers. However, these methods have limitations such as computational complexity, complex control strategies, and accuracy in measuring control variables. In [22-24], a 12-pulse rectifier using a passive auxiliary circuit installed in the DC link is presented. In this method, the interphase reactor is replaced with a tapped interphase reactor. In [23], a 12-pulse rectifier connected in parallel with a two-tap interphase reactor and two diodes is proposed. When a double-tap inductor is used, the sum of the current passing through two diodes connected to the double-tap interphase reactor is equal to the load current, which leads to an increase in losses passing through the diodes in large load currents. To improve the power quality indicators in [25], a 20-pulse rectifier is proposed although its kVA rate is 35.3% of the load.

In [26], a 44-pulse rectifier based on a 22-phase polygon transformer is presented. This structure requires 44 diodes and a very complex transformer with several turns. Therefore, the method for reducing harmonics using an APTC is a simple, inexpensive method to achieve the above goal. In addition, because the magnetic part of the transformer used in multi-pulse rectifiers constitutes a major part of the dimensions, weight, and cost of multi-pulse rectifiers, in most non-isolated applications of the autotransformer due to the reduction of the magnetic part by about 80% compared to the transformer and as a result reducing dimensions, weight, losses, and cost of multi-pulse rectifier is used. With this approach, a 12-pulse rectifier based on a polygonal autotransformer with a low kVA rating is designed. This 12-pulse rectifier is then upgraded to an optimal 36-PAR using a low-complexity APTC. In terms of technical and economic indicators, it has been improved compared with the existing 36-PARs [27-29]. The comparison of existing multi-pulse rectifiers

TABLE 1
COMPARISON OF THE EXISTING MPRS

Part	20-Pulse [8]	20-Pulse [10]	20-Pulse [31]	24-Pulse [22]	24-pulse [24]	36-Pulse [15]	36-Pulse [28]	40-pulse [9]	40-pulse [36]	40-pulse [14]	44-Pulse [26]	48-pulse [35]	Proposed 36-pulse
% of THD	3.04	3.70	3.71	6.74	5.25	3.12	3.9	2.55	0.8	2.67	1.55	3.13	1.44
Total kVA Rating of the Autotransformer (Load Rating %)	40.27	45.47	44.48	39.7	115.00	30.30	44.15	63.98	31.88	30.8	42	31.57	24.08
Diode	20	20	20	10	14	16	36	42	28	20	32	30	18
Approximate total cost ($)	226.2	249.6	245.2	201.2	549.7	172.5	279.5	382.4	206.5	183.6	261	209.5	148.8

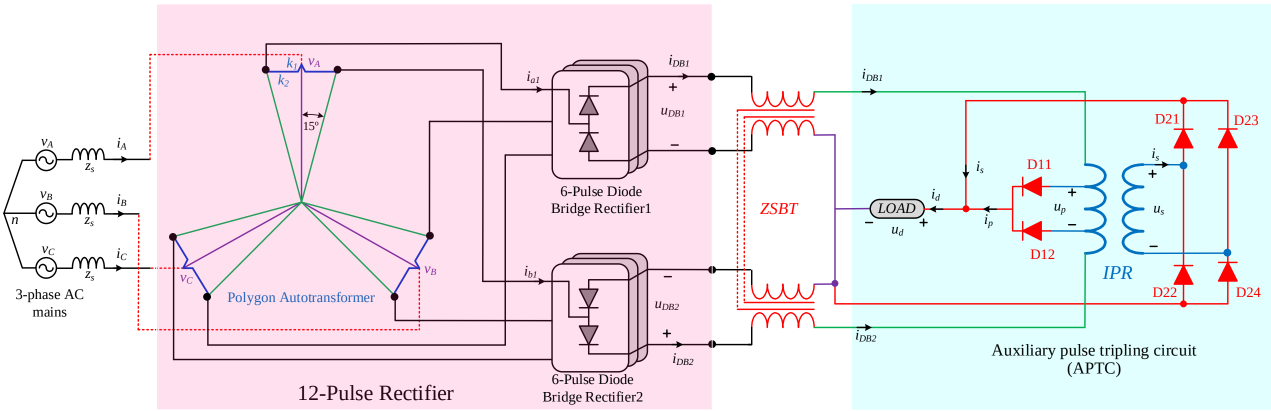


Fig. 1. 12-PAR with APTC

(MPRs) in terms of input current THD percentage, kVA rate, number of diodes, and approximate cost is presented in Table 1. Note that to estimate the cost of MPRs in this table, similar to the thumb estimation method in [36], it is calculated by multiplying the percentage of the kilovolt-ampere rate by 4.5. In addition, the cost of each diode is estimated to be $2.25. As can be seen in Table 1, with the increase in the number of pulses, the ability to reduce the harmonic distortion of the input current increases so that the 40-pulse rectifier [36] has a THD of the input current less than 1%. Note that transformer-based MPRs [24] have a kilovolt-ampere rate of more than 100%; as a result, they are more expensive than autotransformer-based MPRs. Also, the proposed 36-PAR has the lowest kilovolt-ampere rate equal to 24.08% of the load power, and as a result, the lowest cost is equal to 148.8.

II. Proposed 36-PAR design

The proposed 36-PAR consists of two parts (as shown in Fig. 1). The first part of the 12-PAR is based on a six-phase polygon connection, and the second part is the APTC to upgrade the structure of the 12-PAR to 36-PAR.

A. *Six-phase autotransformer design based on polygon autotransformer*

The 18-phase polygon autotransformer [28] used in conventional 36-PAR is shown in Fig. 2 (a). As can be seen in this figure, the autotransformer has two 9-phase voltage series with a 10-degree phase shift. The structure of this autotransformer is very complex and includes several windings, which increases the kilovolt ampere rate of the autotransformer. The connections of the polygon autotransformer used in 12-PAR are shown in Fig. 2 (b). As can be seen in Fig. 2, the structure and number of windings of the 6-phase autotransformer in the 12-PAR is much simpler and lighter than the structure of the conventional 36-PAR [28].

The 12-PAR is based on a six-phase polygon autotransformer with a low kilovolt-ampere rate and a small weight and size. The minimum phase shift required to remove inappropriate harmonics is shown in equation (1):

$$\text{phase shift} = \frac{\text{Number of six pulse rectifiers}}{60^{\circ}} \quad (1)$$

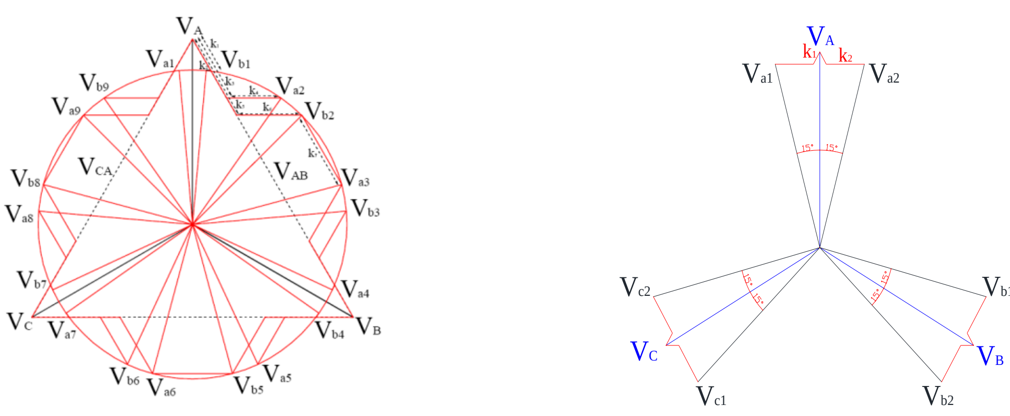


Fig. 2. Connections of the polygon autotransformer in (a) conventional 36-PAR [28] and (b) 12-PAR

Considering that in the 12-PAR, two conventional 6-pulse rectifiers have been used, according to equation (1), the phase shift between two series of voltages should be considered 30 degrees. The six-phase autotransformers produce 2 sets of three phases with 30 phase shifts for each diode bridge of six pulses.

The three-phase voltage of the source is as follows:

$$V_A = V_S\measuredangle 0^\circ, V_B = V_S\measuredangle -120^\circ, V_C = V_S\measuredangle +120^\circ \quad (2)$$

Two voltage series with 30-degree phase shift output of the 6-phase autotransformer:

$$V_{a1} = V_S\measuredangle 15^\circ, V_{b1} = V_S\measuredangle -105^\circ, V_{c1} = V_S\measuredangle 135^\circ, V_{a2} = V_S\measuredangle -15^\circ, V_{b2} = V_S\measuredangle -135^\circ, V_{c2} = V_S\measuredangle 105^\circ \quad (3)$$

V_{a1} and V_{a2} are expressed as follows according to the winding ratio of the autotransformer:

$$\begin{cases} V_{a1} = V_A + K_1 V_{CA} - K_2 V_{BC} \\ V_{a2} = V_A - K_1 V_{AB} + K_2 V_{BC} \end{cases} \quad (4)$$

Considering equations 2 to 4, the constant values of K_1-K_2 are calculated. Due to the performance of the proposed 36-PAR, the DC link voltage is approximately 1.03% equal to the DC link voltage of the conventional 6-pulse rectifier. To use the proposed converter in alternative applications (applications that require exactly the DC link voltage equal to 6-pulse diode bridge rectifiers), the design of the proposed converter should be modified appropriately. For this purpose, the output voltage level of the polygon autotransformer should be 0.03 Decrease. The modified values of the coefficients for the performance of the proposed rectifier in alternative applications are calculated as follows:

$$K_1 = 0.0472, K_2 = 0.1201 \quad (5)$$

The above equations show the values of the constants K_1-K_2 (number of winding turns) as a fraction of the effective input voltage of the autotransformer. These values are used to simulate and build the autotransformer. the proposed polygon autotransformer. As can be seen in this figure, the output voltage of the autotransformer is a two-voltage series with a phase angle of 30 degrees. These two voltage series are connected to two conventional six-pulse diode bridges, which leads to the creation of a 12-PAR rectifier, which is then upgraded to a 36-PAR using an APTC.

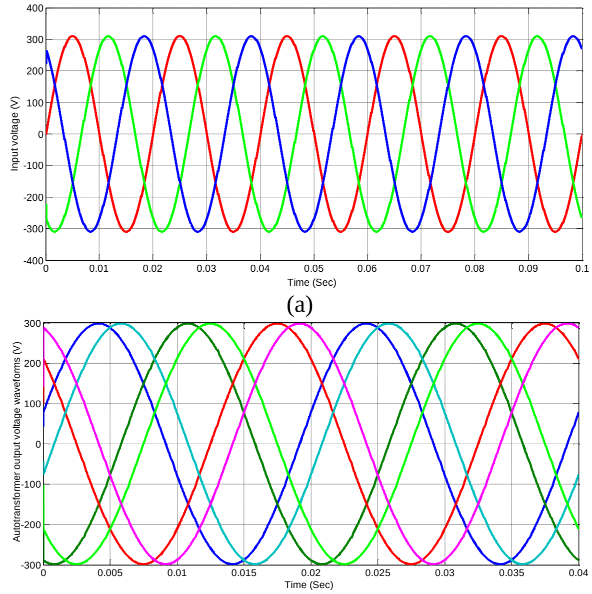


Fig. 3. (a) input and (b) output voltages of the autotransformer

B. Design of the proposed APTC

As shown in Fig. 1, the proposed APTC is used to

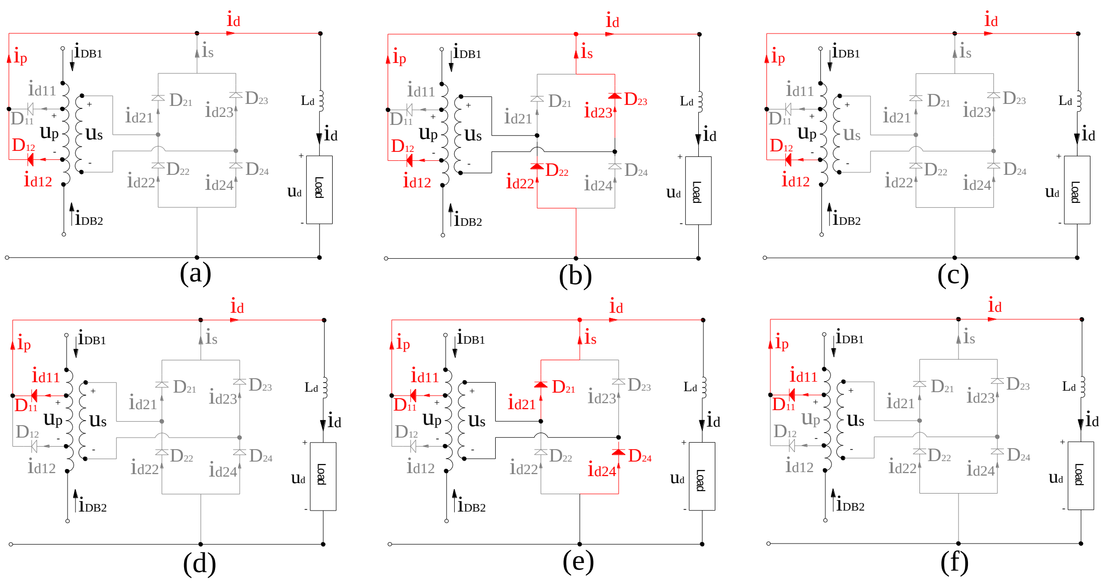


Fig. 4. Operating modes of the proposed APTC

upgrade the 12-PAR to the 36-PAR. this APTC consists of an unconventional interphase transformer (UIPT) with two diodes in the primary winding and a single-phase diode bridge rectifier connected to the secondary winding.

When u_p>0, diode D_{11} is on, and when u_p<0, diode D_{12} is on. In addition, when $|u_s|<u_d$, diodes D_{21}, D_{22}, D_{23}, and D_{24} are in reverse bias and off. When $u_s>u_d$, diodes D_{21} and D_{24} are forward biased and on, and diodes D_{22} and D_{23} are reverse biased and off. When $-u_s>u_d$, diodes D_{21} and D_{24} are in reverse bias and off, and diodes D_{22} and D_{23} are in forward bias and on. Therefore, based on the above points, as shown in Fig. 4, the proposed APTC has six operating modes. The mathematical relationships related to the working modes of the APTC (Fig. 4) are presented in Table 2. Note that the coefficients α and m in this table are the tap winding ratio and the turn ratio of the UIPT, respectively.

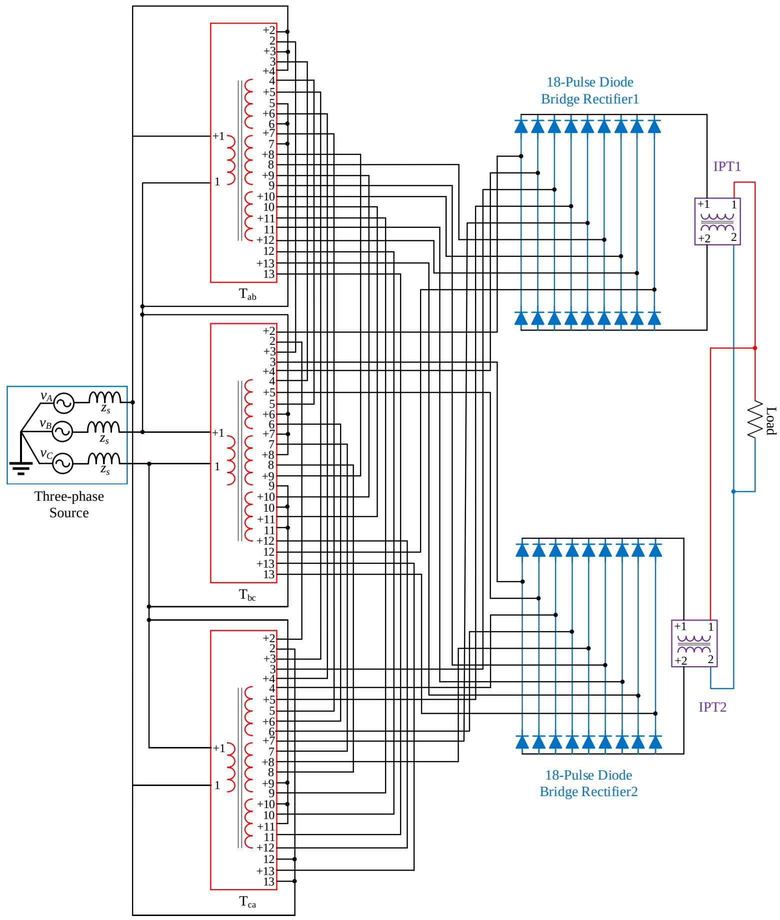
III. Modeling and simulation of the proposed 36-PAR

This section includes the software modeling and simulation of the 6-phase autotransformer based on polygon connection and the APTC to achieve the proposed 36-PAR in MATLAB-Simulink software. In the simulation, a source with a line voltage of 460 V and a frequency of 50 Hz and a load with a power of 30 kW and a voltage of 600 V are considered. In addition, the sum of the source impedance and the leakage inductance of the autotransformer is approximately equal to 5 mH. The sum of the inductances of ZSBT and UIPT is also considered to be approximately 20 mH. As shown in Fig. 5, the autotransformer structure of the proposed 36-PAR (Fig. 5-b) is much simpler and lighter with a lower kilovolt-ampere rate than conventional 36-PARs (Fig. 5-a). In addition, the number of diodes used in the structure of the proposed 36-PAR is less, and as a result, the conduction loss in the proposed rectifier is less than that in the conventional 36-PAR.

The results of the simulation completely confirm the performance of the different parts of the proposed design (the performance of the 6-phase autotransformer as well as the performance of the APTC). Figs. 6 and 7 show the input and output current and voltage waveforms of the proposed APTC, respectively. Note that in the APTC, the ratio of the turns of the transformer winding with an unconventional winding is approximately equal to 12 (Fig. 6), which leads to a decrease in the current passing through the secondary

TABLE 2.
WORKING MODES OF THE APTC

Mode	Fig.	KVL	KCL	Diode11	Diode12	Diode21	Diode22	Diode23	Diode24
1	4 (a)	$u_d = 0.5(u_{DB1} + u_{DB2})$	$\begin{cases} i_{DB1} = 0.5i_d - \alpha i_d \\ i_{DB2} = 0.5i_d + \alpha i_d \end{cases}$	Off $i_{D11} = 0$	On $i_{D12} > 0$	Off $i_{D21} = 0$	Off $i_{D22} = 0$	Off $i_{D23} = 0$	Off $i_{D24} = 0$
2	4 (b)	$\begin{cases} u_d = -u_s = \frac{2m}{2m+1-2\alpha} u_{DB2} \\ u_{DB1} = \frac{2m-1-2\alpha}{2m+1-2\alpha} u_{DB2} \\ u_p = -\frac{2}{2m+1-2\alpha} u_{DB2} \end{cases}$	$\begin{cases} i_s = \frac{1-2\alpha}{2m+1-2\alpha} i_d \\ i_{DB2} = \frac{2m}{2m+1-2\alpha} i_d \\ i_{DB1} = 0 \end{cases}$	Off $i_{D11} = 0$	On $i_{D12} > 0$	Off $i_{D21} = 0$	On $i_{D22} > 0$	On $i_{D23} > 0$	Off $i_{D24} = 0$
3	4 (c)	$u_d = 0.5(u_{DB1} + u_{DB2})$	$\begin{cases} i_{DB1} = 0.5i_d - \alpha i_d \\ i_{DB2} = 0.5i_d + \alpha i_d \end{cases}$	Off $i_{D11} = 0$	On $i_{D12} > 0$	Off $i_{D21} = 0$	Off $i_{D22} = 0$	Off $i_{D23} = 0$	Off $i_{D24} = 0$
4	4 (d)	$u_d = 0.5(u_{DB1} + u_{DB2})$	$\begin{cases} i_{DB1} = 0.5i_d + \alpha i_d \\ i_{DB2} = 0.5i_d - \alpha i_d \end{cases}$	On $i_{D11} > 0$	Off $i_{D12} = 0$	Off $i_{D21} = 0$	Off $i_{D22} = 0$	Off $i_{D23} = 0$	Off $i_{D24} = 0$
5	4 (e)	$\begin{cases} u_d = u_s = \frac{2m}{2m+1-2\alpha} u_{DB1} \\ u_{DB2} = \frac{2m-1-2\alpha}{2m+1-2\alpha} u_{DB1} \\ u_p = -\frac{2}{2m+1-2\alpha} u_{DB1} \end{cases}$	$\begin{cases} i_s = \frac{1-2\alpha}{2m+1-2\alpha} i_d \\ i_{DB1} = \frac{2m}{2m+1-2\alpha} i_d \\ i_{DB2} = 0 \end{cases}$	On $i_{D11} > 0$	Off $i_{D12} = 0$	On $i_{D21} > 0$	Off $i_{D22} = 0$	Off $i_{D23} = 0$	On $i_{D24} > 0$
6	4 (f)	$u_d = 0.5(u_{DB1} + u_{DB2})$	$\begin{cases} i_{DB1} = 0.5i_d + \alpha i_d \\ i_{DB2} = 0.5i_d - \alpha i_d \end{cases}$	On $i_{D11} > 0$	Off $i_{D12} = 0$	Off $i_{D21} = 0$	Off $i_{D22} = 0$	Off $i_{D23} = 0$	Off $i_{D24} = 0$



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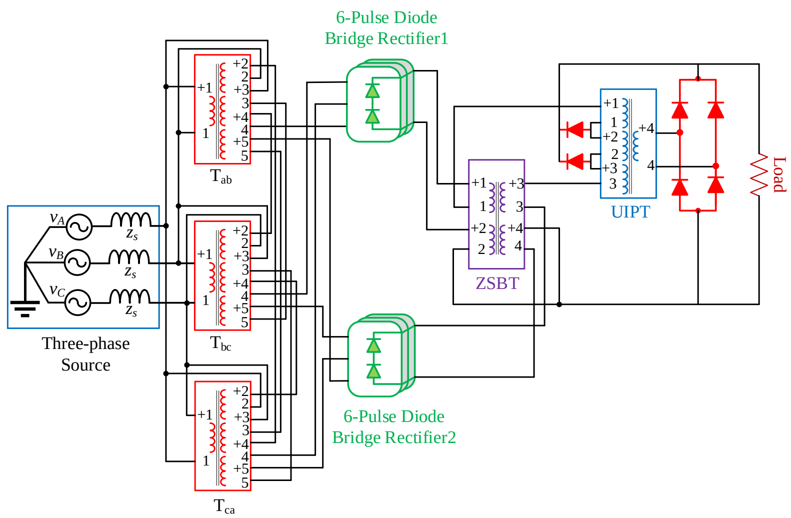
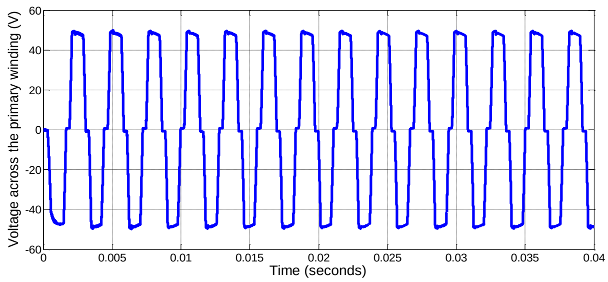


(b)

Fig. 5. MATLAB-Simulink model: (a) conventional 36-pulse rectifier [27] and (b) proposed 36-pulse rectifier

winding of the UIPT winding (Fig. 7-b). This form confirms the accuracy of the design and modeling of the APTC. The output voltage waveform of two conventional six-pulse diode bridges with a phase difference of 30 degrees is shown in Fig. 8, and the output voltage/current of the proposed 36-PAR is shown in Fig. 9. As can be seen in Fig. 9, the DC voltage/current of the proposed rectifier has 36-pulse in the output and is almost smooth with very little ripple, which confirms the performance of the different parts of the proposed rectifier.



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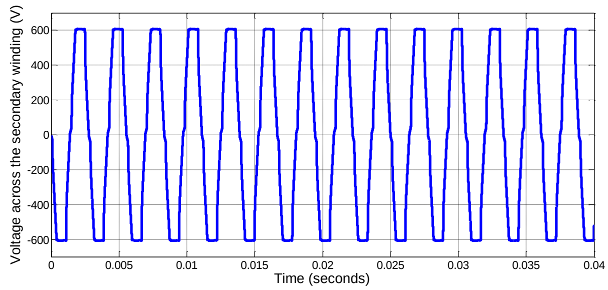
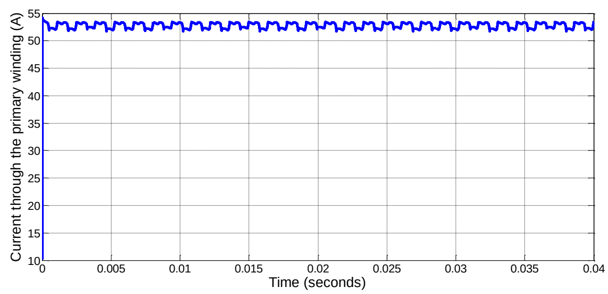


(b)

Fig. 6. (a) Input and (b) output voltage waveforms of the APTC



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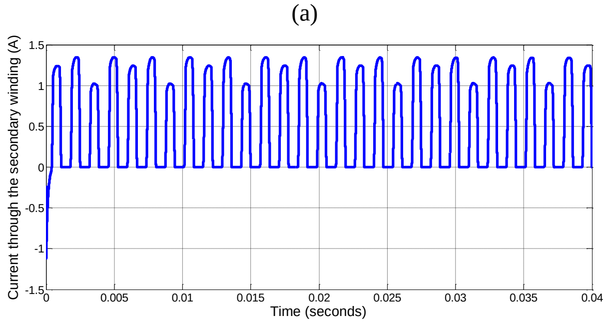


(b)

Fig. 7. (a) Input and (b) output current waveforms of the APTC

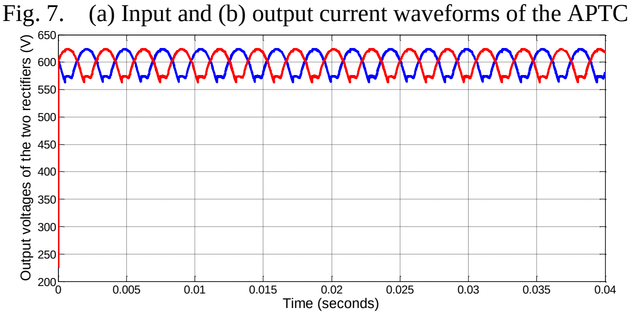
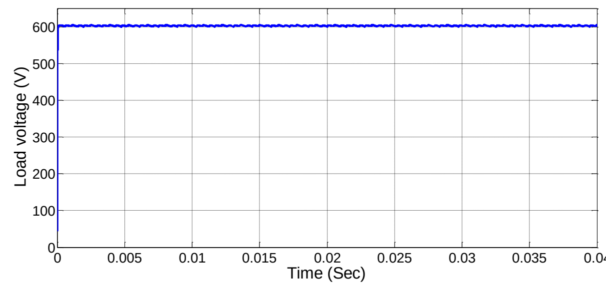


Fig. 8. Output voltage waveform of the two six-pulse diode bridges



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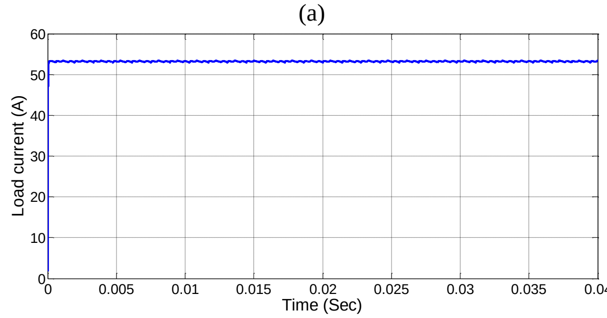
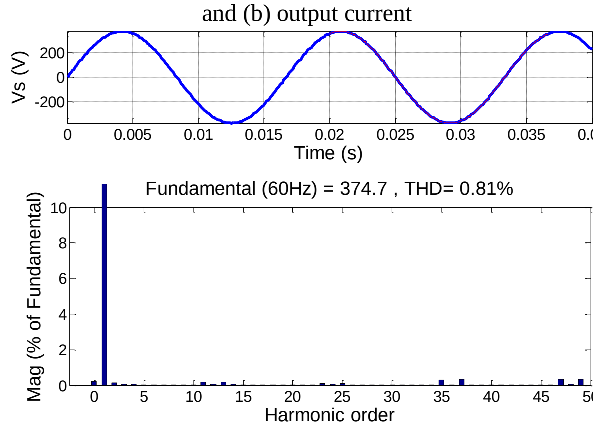


(b)

Figure 9. Waveforms of the proposed 36-PAR: (a) output voltage and (b) output current



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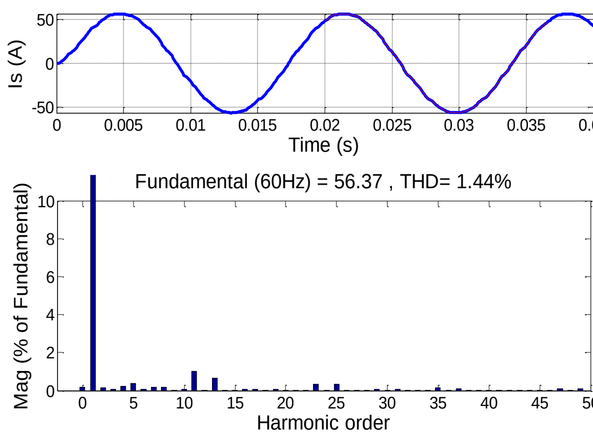
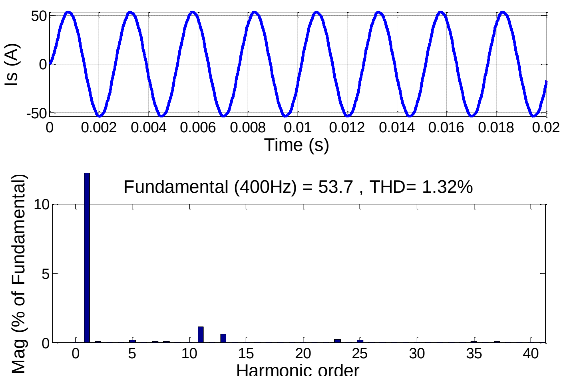


(b)

Fig. 10. Waveform and harmonic spectrum of the proposed 36-PAR at full load: (a) input voltage and (b) input current

The current THD in the six-pulse rectifier [33] is 3.3%. Fig. 10 shows the input current and voltage with the harmonic spectrum of the proposed 36-PAR. As can be seen in this figure, the harmonic distortion of the voltage is equal to 1.03% and that of the current is equal to 1.4%. The results show that the proposed rectifier performs well in reducing the harmonic distortion of the input current and voltage. To reduce the IC-THD in aviation applications, a 20-pulse rectifier and an 18-pulse rectifier are proposed in [31]. However, it should be noted that both of these rectifiers require the use of input and output filters to meet the requirements of the DO-160G standard. If the IC-THD in the proposed 36-PAR based on the APTC is less than 3% and without the need for a filter, it can meet the requirements of the DO-160G standard. To check the feasibility of using the proposed rectifier in aviation applications, the results of the harmonic distortion of the current by separating the odd and even harmonic orders and considering the allowed values of the DO-160G standard are shown in Fig. 11 for the source frequency of 400 Hz and Fig. 12 for the frequency 800 Hz source. As shown in Figs. 11 and 12, the proposed 36-PAR can meet the requirements of the DO-160G standard in even- and odd-order harmonics without the need for a filter. The results confirm the high efficiency of the proposed rectifier in aviation applications.



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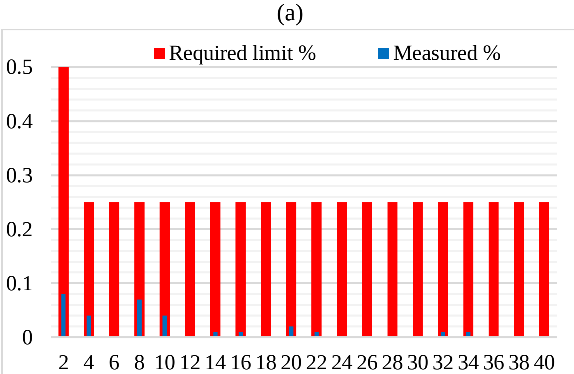

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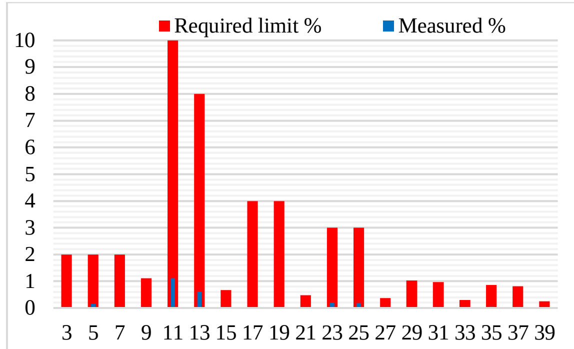
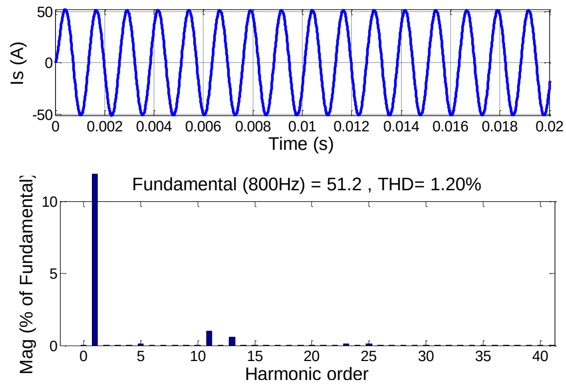
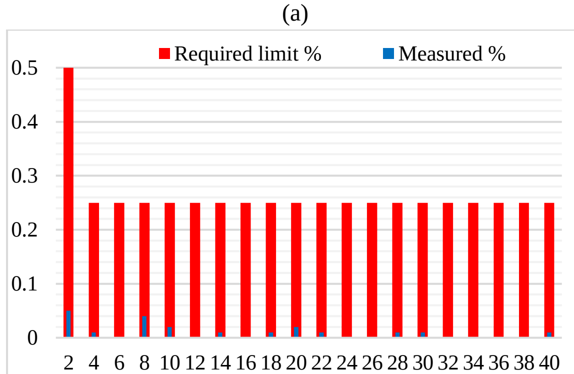


(c)

Fig. 11. (a) Input current along with its harmonic spectrum at a source frequency of 400 Hz, (b) even-order harmonics, and (c) odd-order harmonics compared to the DO-160G standard limit.



(a)



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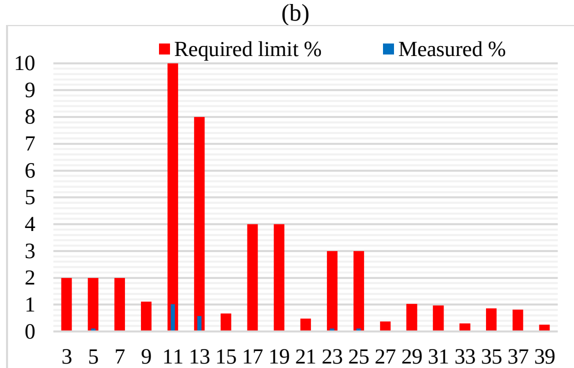


(c)

Fig. 12. (a) Input current along with its harmonic spectrum at a source frequency of 800 Hz, (b) even-order harmonics, and (c) odd-order harmonics compared to the DO-160G standard limit.

IV. kilovolt-ampere rate

The rms values of the winding voltage and current of the six-phase polygon autotransformer, the zero sequences blocking circuit (ZSBT), which is used to isolate the output voltages of two six-pulse rectifiers, and the rms values of the winding voltage and current of the UIPT winding for a 10 kVA load were calculated by software simulation. Based on these values and equation (6), the kilovolt-ampere rate of the proposed rectifier is calculated.

$$S = 0.5 \sum V_{winding} I_{winding} \quad (6)$$

The kilovolt-ampere rate of the polygon autotransformer is equal to 1809.39 volts, ZSBT is equal to 464.72, and UIPT is equal to 134.77. In total, considering the rated load power of 10 kV, the kilovolt-ampere rate of the proposed 36-PAR is equal to 24.08% of the rated load power. Fig. 13 shows a comparison of the proposed 36-PAR with conventional 36-PARs [27-30] in terms of the kilovolt-ampere rate and harmonic distortion percentage of the total current at full and light loads (equivalent to 20% of full load). As can be seen in this figure, the kilovolt-ampere rate of the proposed rectifier is far lower than that of conventional 36-PARs. The kilovolt-ampere rate of the proposed rectifier is approximately 19.14%, 19.84%, 37.82%, and 6.43% lower than the kVA rating of 36-PARs [27], [28], [29], and [30], respectively. In addition, the harmonic distortion of the current in conventional 36-PARs [27-30] under light load is more than 3%, whereas, in the proposed 36-PAR, the harmonic distortion of the current is always less than 3% and conforms to MIL-STD 704F and IEEE-519 standards. This confirms the high technical and economic capabilities of the proposed rectifier compared with conventional 36-PARs.

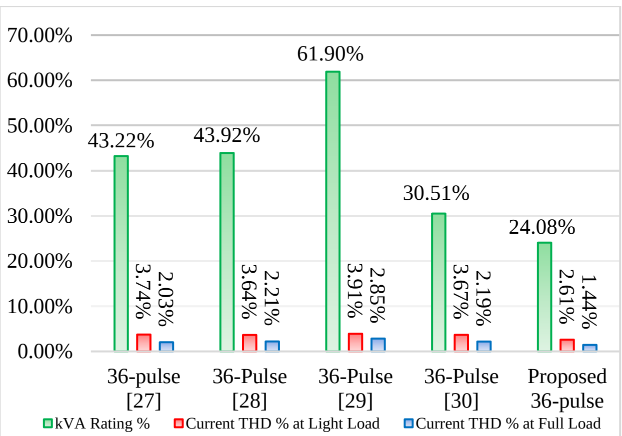
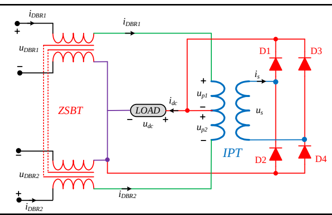
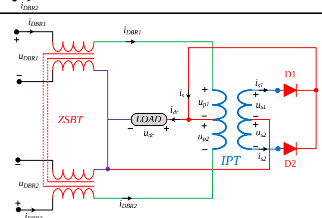
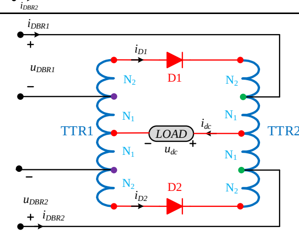
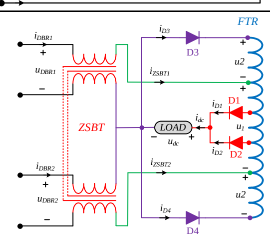


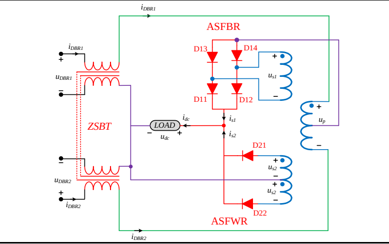
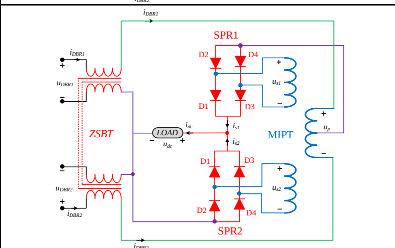
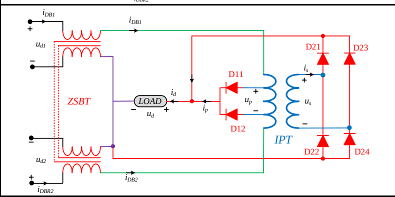
Fig. 13. Comparison of the kVA and current harmonic distortion in the proposed 36-pass rectifier with conventional 36-PARs

V. Comparison of the proposed APTC with existing harmonics-reducing circuits

In this section, to evaluate the structure of the APTC used in the proposed 36-PAR with existing harmonic reducing circuits, the structure of various types of harmonic reducing circuits along with the kilovolt-ampere rate and the number of diodes of each of the structures are listed in Table 3. As can be seen in this table, the existing harmonic reducing circuits have 2 to 8 diodes, and in this sense, the proposed APTC includes 6 diodes. In addition, the kilovolt-ampere rate of the proposed APTC is equal to 5.99% of the full load power, which is lower than the kilovolt-ampere rate of the existing harmonic reduction circuits. The approximate cost of the proposed APTC is $40.5, which is acceptable compared to the cost of existing harmonic reduction circuits.

TABLE 3.
COMPARISON WITH SIMILAR HARMONIC REDUCTION CIRCUITS

References	Topologies	Total kVA rating (%)	Number of Diodes	Total Cost ($)
[22]		9.84	4	53.3
[24]		8.04	2	40.7
[34]		11.27	2	55.2
[34]		6.97	4	40.4

[35]		7.57	6	47.6
[36]		6.98	8	49.4
Proposed		5.99	6	40.5

VI. Conclusion

In this paper, a proposed 36-PAR based on a 6-phase autotransformer with an APTC with a low kilovolt-ampere rate is presented. These two advantages have led to savings in the size and cost of the proposed 36-PAR compared to other conventional 36-PARs. The simulation results show that in addition to meeting the requirements of the IEEE 519 standard, the IC-THD in the proposed 36-PAR is less than 3% and conforms to the MIL-STD standard. Also, the results confirm the performance of the proposed 36-PAR under the requirements of the DO-160G standard in aviation applications without the need for a filter. The proposed 36-PAR kilovolt-ampere rate is 24.08% of the rated load power. In general, the proposed 36-PAR is superior both technically and economically compared to other conventional 36-PARs.

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