JPE 18-5-22

https://doi.org/10.6113/JPE.2018.18.5.1536
ISSN(Print): 1598-2092 / ISSN(Online): 2093-4718

Step-up and Step-down Asymmetrical 24-Pulse Autotransformer Rectifier

Lu Zhang[†], Hong-juan Ge[*], Fan Jiang[*], Guang Yang[*], and Yi Lin[*]

[†,*]Nanjing University of Aeronautics and Astronautics, Nanjing, China

Abstract

The existing 24-pulse autotransformer rectifier unit (ATRU) needs interphase reactors for parallel work of the rectifier bridges, and its output voltage cannot be regulated. Aiming at these problems, a step-up and step-down asymmetrical 24-pulse ATRU is proposed in this paper. The connections and turns ratios among transformer windings are well designed. In addition, a 15-degree phase difference is formed between two of the 24 voltage vectors produced by the transformer, which makes the four rectifier bridge groups produce a 24-pulse DC voltage without interphase reactors. Meanwhile, by adding extended winding to each phase of the transformer, wide-range regulation of the ATRU output voltage can be realized, and the reasonable voltage regulation range is between 0.2 and 1.6. The superposition of the voltage vectors and the principle of the voltage regulation are analyzed in detail. Furthermore, the turns ratio of the windings, winding current, output voltage, and kilovolt-ampere rating are all derived. Finally, the simulations and experiments are carried out, and the correctness of the principle and theoretical analysis of the new 24-pulse ATRU are verified.

Key words: 24-pulse, Autotransformer rectifier, Kilovolt-ampere rating, Voltage regulation

I. Introduction

To suppress the harmonic content in the power supply systems, multi-pulse technology has been used in a variety of situations [1]-[4], and the autotransformer rectifier unit (ATRU) has had a wide range of applications. An ATRU can omit or simplify the filter unit, and has the advantages of close coupling, small volume, light weight, high efficiency and so on [5]-[8]. The 24-pulse ATRU, which has a greater advantages in terms of harmonic suppression when compared with the 12-pulse and 18-pulse ATRUs, has become a hot spot in the field of multi-pulse technology. Through some improvements and optimization, voltage regulation within a certain range can extend the application range of the 24-pulse ATRU. Thus, the ATRU can be applicable to various DC power supply fields powered by three-phase mains.

The existing 24-pulse ATRUs are mostly delta or wye connected. The delta connected 24-pulse ATRU was proposed in [9]. Its kilovolt-ampere rating is 17.3%, and the THD of its input current is 7.6%. The wye connected 24-pulse ATRU was proposed in [10]. Its kilovolt-ampere rating is 27.08%, and the THD of its input current is 7.5%. When compared with 12-pulse and 18-pulse ATRUs, the input current THD of existing 24-pulse ATRUs is decreased a lot [11]. However, because interphase reactors are required for the parallel work of rectifier bridges, the complexity and volume weight of 24-pulse ATRUs are greatly increased [12].

For voltage regulation, most of the existing studies are carried out based on the differential triangle structure. The voltage regulation of ATRUs based on the wye-topology and delta-topology are studied in [13]. According to [13], the ATRU output voltage can be adjusted by changing the turns ratio of the secondary windings. The influence of the secondary winding tap position on the value of ATRU output voltage is analyzed in [14]. In [15], the output voltage was increased by 1.414 times by changing the phase shift angle of the autotransformer. However, the times of the output voltage gain are invariable. In [16], the voltage gain ranges of the DT-typology and P-typology ATRU are 0.97-2 times and 0.97-1.42, respectively. It can be seen that the voltage regulation method introduced in [16] is undesirable for voltage step-down.

When compared with conventional ATRUs, the new asymmetric P-typology 24-pulse ATRU proposed in this

Manuscript received Nov. 14, 2017; accepted Apr. 16, 2018
Recommended for publication by Associate Editor Yijie Wang.
[†]Corresponding Author: 2447445673@qq.com
Tel: +86-15850656601, Nanjing Univ. of Aeronautics and Astronautics
[*]Nanjing University of Aeronautics and Astronautics, China

paper has two main advantages. First, the DC voltage can be obtained directly by four parallel rectifier bridges without interphase reactors, which can effectively reduce the ATRU volume and weight. Second, the output voltage can be adjusted in a wide range by adding extending windings.

This paper is organized as follows. The new ATRU typology and the principles of the voltage step-up and step-down are introduced in Section II. In addition, the main and auxiliary output voltage vectors of the autotransformer are obtained by synthesizing winding voltage vectors. The vector composition method and the turns ratio of the windings are analyzed in Section III. The currents through the autotransformer windings and the kilovolt-ampere rating of the ATRU are analyzed in Section IV. The feasibility of the design can be verified by simulations and experiments in Section V. Finally, some conclusions are given in Section VI.

II. NEW 24-PULSE ATRU TYPOLOGY

A. Asymmetric 24-Pulse ATRU Topology

The topology of the new asymmetric 24-pulse ATRU is shown in Fig. 1(a). The ATRU is composed of a 24-pulse autotransformer and four rectifier bridges (one main bridge and three auxiliary bridges). There are five windings in each phase; two windings with a middle tap respectively in the primary side, and two short windings and one long winding with a middle tap in the secondary side. The terminals a, b and c in Fig. 1(a) are the input terminals for the three-phase voltage.

As shown in Fig. 1(a), assume that the numbers of turns of the primary windings are N_{p1}, N_{p2}, N_{p3} and N_{p4}, respectively. a_{p1}, a_{p2}, a_{p3} and a_{p4} are the four terminals of the primary windings in A phase. They are connected to the corresponding secondary windings in B phase and C phase. The middle taps a_1 and a_3 are the A-phase input terminals of the uxiliary bridge 1 and auxiliary bridge 3, respectively. Assume that the numbers of turns of the secondary windings are N_{s1}, N_{s2}, N_{s3} and N_{s4}, respectively. There are 7 terminals in the secondary side of each phase. c is the C-phase input terminal of the main bridge. b_2 and c_2 are the B-phase input terminal of auxiliary bridge 2 and the C-phase input terminal of auxiliary bridge 2, respectively. The other terminals in the secondary side are connected to the corresponding primary windings. The terminals in B phase and C phase are similar.

The voltage vectors of the windings in the same phase are parallel. Therefore, a voltage vector diagram of the new autotransformer can be obtained, as shown in Fig. 2.

B. Principle of Voltage Step-Up and Step-Down

On the basis of the 24-pulse ATRU topology, adding an extending winding to each phase can make the ATRU output voltage adjustable. The topology shown in Fig. 1(b) can realize voltage step-down. In Fig. 1(b), the extending windings are indicated in red, and the number of turns for each of the extending windings is N_{p0}. Fig. 3(a) shows the corresponding vector diagram, where the extending winding voltage vectors are shown in red. Thus, the three-phase input voltage terminals change to A, B and C.

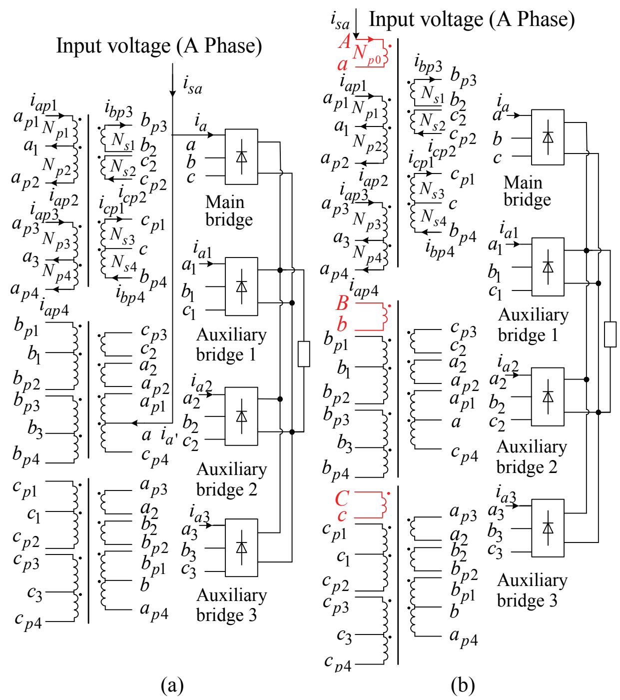

Fig. 1. Asymmetric 24-pulse ATRU topology.

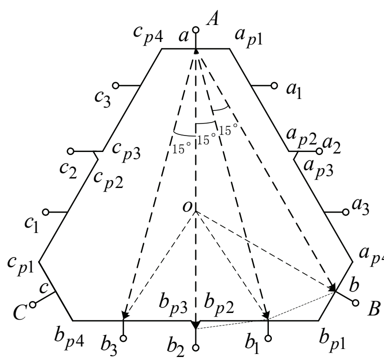

Fig. 2. Voltage vectors of a 24-pulse ATRU.

A phase is taken as an example to explain the principle of voltage step-down. Without extending windings (Fig. 2), the output main phase voltage of the autotransformer is equal to its input phase voltage. As a result, $\vec{V}_{oA} = \vec{V}_{oa}$. When extending winding is added to each phase (Fig. 3(a)), the output main phase voltage of the autotransformer is composed of its input phase voltage and the voltage across the extending winding. Assuming $\vec{V}_{Aa}$ is k times longer than $\vec{V}_{ab}$, the following equation can be obtained:

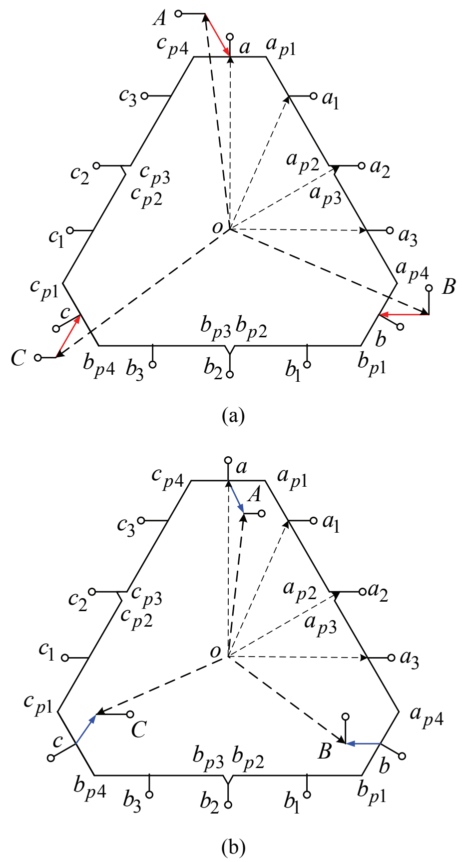

Fig. 3. Voltage vectors of step-up and step-down 24-pulse ATRUs: (a) Voltage vectors of a step-down 24-pulse ATRU, (b) Voltage vectors of a step-up 24-pulse ATRU.

$$\vec{V}_{oa} = \vec{V}_{oA} + k\vec{V}_{ab} \quad (1)$$

When the length of $\vec{V}_{oA}$ is constant, the length of $\vec{V}_{oa}$ decreases with an increase in the value of k. At the same time, the length ratios of $\vec{V}_{oa}$ and the other output voltage vectors remain the same to realize voltage step-down.

By changing the dotted terminal of the extending winding, the voltage vector of the extending winding can be reversed. Therefore, voltage step-up can be realized. Fig. 3 (b) shows a voltage vector diagram for the voltage step-up, in which the extending winding voltage vectors are shown in blue. Combined with the voltage step-down previously mentioned, the scheme of adding an extending winding to each phase can adjust the 24-pulse ATRU output voltage in a wide range.

This voltage regulation scheme has few side effects on the input-output performance of the 24-pulse ATRU. In particular, the extending winding does not increase the total harmonic distortion (THD) of the input current, which can ensure a good input performance. However, when the transformer works in step-up or step-down situations, its kilovolt-ampere rating increases. In principle, this is unavoidable due to voltage regulation. Detail information is presented in Section 4 and Section 5.

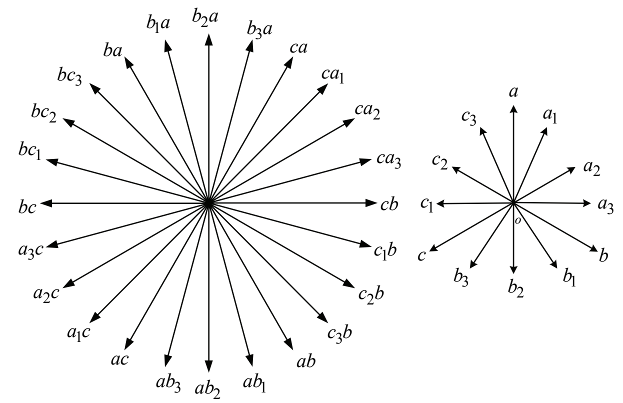

Fig. 4. Main and auxiliary voltage vectors.

III. Autotransformer Winding

As shown in Fig. 4, the 24-pulse autotransformer generates a group of three-phase main voltage vectors ($\overrightarrow{oa}, \overrightarrow{ob}, \overrightarrow{oc}$) and three groups of three-phase auxiliary voltage vectors ($\overrightarrow{oa_1}, \overrightarrow{ob_1}, \overrightarrow{oc_1}$), ($\overrightarrow{oa_2}, \overrightarrow{ob_2}, \overrightarrow{oc_2}$), ($\overrightarrow{oa_3}, \overrightarrow{ob_3}, \overrightarrow{oc_3}$). The main and auxiliary voltages supply the rectifier bridges and make the diodes conduct in different time zones. The output voltage of the ATRU, a 24-pulse DC voltage, is composed of a superposition of the transformer output voltages in different time zones. The output line voltage vectors are of equal length with a 15° phase difference between adjacent vectors. For example, the line voltage vector $\overrightarrow{ab}$ is the superposition of $-\overrightarrow{oa}$ and $\overrightarrow{ob}$, and the line voltage vector $\overrightarrow{ab_1}$ is the superposition of $-\overrightarrow{oa}$ and $\overrightarrow{ob_1}$. It can be seen that the lengths of $\overrightarrow{ab}$ and $\overrightarrow{ab_1}$ are equal, and that there is a 15° angle between the two vectors. Similarly, it is possible to obtain all of the other line voltage vectors in Fig. 4 such as $\overrightarrow{ab_2}$, $\overrightarrow{ab_3}$, etc.

In each time zone, only two diodes are turned on. The four groups of rectifier bridges can directly work in parallel. Thus, the interphase reactors can be omitted. The main rectifier bridge works all of the time, where each diode is continuously turned on for 75° in one cycle. Each diode in the auxiliary rectifier bridges is turned on only for 15° in one cycle when the instantaneous value of the corresponding line voltage reaches the maximum. Therefore, the input current waveform for each of the diodes in the main rectifier is a square wave with a duty cycle of 20.83%. In addition, the input current waveform for each of the diodes in the auxiliary rectifiers is a square wave with a duty cycle of 4.17%.

To ensure that the value of the ATRU output voltage is nearly constant, the amplitude for each of the output line voltages of the autotransformer should be equal. Therefore, the turns ratio of the autotransformer windings should be rationally designed. According to transformer theory, the turns ratio of the windings is equal to their voltage ratio. Therefore, the turns ratio of the windings (except for the extending windings) can be deduced by Fig. 2 and Fig. 4. In order to simplify the calculation, assume that the length of the vector $\overrightarrow{oa}$ is 1. It can be calculated that $bb_{p1}=0.2$, $b_{p1}b_1=0.317$, $b_1b_{p2}=0.414$ and $b_{p2}b_2=0.068$. Thus, the turns ratios of the windings are expressed.

$$\begin{cases}\dfrac{N_{p1}}{N_{p2}}=\dfrac{N_{p1}}{N_{p3}}=\dfrac{0.317}{0.414}=\dfrac{1}{1.306}\\ \dfrac{N_{p1}}{N_{s1}}=\dfrac{N_{p1}}{N_{s2}}=\dfrac{0.317}{0.068}=\dfrac{1}{0.215}\\ \dfrac{N_{p1}}{N_{s3}}=\dfrac{N_{p1}}{N_{s4}}=\dfrac{0.317}{0.2}=\dfrac{1}{0.631}\end{cases} \tag{2}$$

When the extending windings are added, the turns ratio calculated above requires no change. The output voltage value of the asymmetrical 24-pulse ATRU depends on the number of turns of the extending windings.

In the situation of a voltage step-down (Fig. 3(a)), the cosine theorem can be used in triangle oaA to work out the relationship among the main output voltage (V_{oa}), the input voltage (V_{oA}) and the extending winding voltage (V_{aA}).

$$\cos 150° = \frac{VaA^2 + Voa^2 - VoA^2}{2 \cdot VaA \cdot Voa} \tag{3}$$

Similarly, in the situation of a voltage step-up (Fig. 3(b)), the relationship is changed as Eq. (4).

$$\cos 30° = \frac{VaA^2 + Voa^2 - VoA^2}{2 \cdot VaA \cdot Voa} \tag{4}$$

Assuming k_u is the ratio of the autotransformer's output main phase voltage value and input phase voltage value ($k_u = \frac{oa}{oA}$), the ATRU output DC voltage can be calculated by Eq. (5), where V_{in} stands for the effective value of ATRU input voltage.

$$V_d = \frac{\int_{7\pi/24}^{9\pi/24} \sqrt{6} V_{oa} \sin(\omega t + \pi/6)\, d(\omega t)}{2\pi/24} = 2.4437 k_u V_{in} \tag{5}$$

IV. Autotransformer Kilovolt-Ampere Rating

A. Currents through the Autotransformer Windings

The following analysis of the winding currents takes voltage step-down as an example. Voltage step-up is similar to this. The A-phase winding connection of a 24-pulse autotransformer is shown in Fig. 5, where the extending windings are indicated in red. The winding connections of the other two phases are similar to A phase.

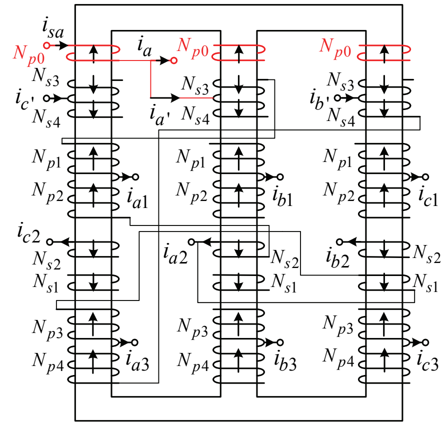

Fig. 5. A-phase winding connection of a step-down autotransformer.

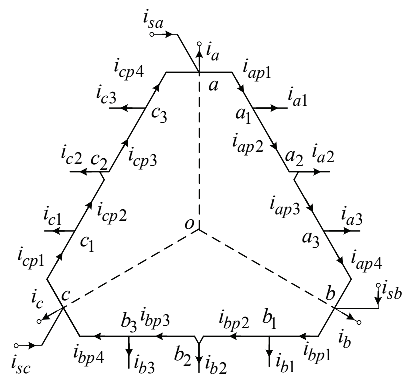

Fig. 6. Winding currents of a step-down autotransformer.

The node currents of the autotransformer are shown in Fig. 6. For A phase, i_{sa} is the A-phase input current of the 24-pulse ATRU. i_{ap1}, i_{ap2}, i_{ap3} and i_{ap4} are the A-phase winding currents of the transformer. i_a, i_{a1}, i_{a2} and i_{a3} are the A-phase output currents of the transformer. The other two phases are similar A-phase.

According to the magnetic circuit balance:

$$\begin{cases}N_{p0}\cdot i_{sa}+N_{p1}(i_{ap1}+i_{ap4})+N_{p2}(i_{ap2}+i_{ap3})=N_{s3}(i_{bp4}+i_{cp1})+N_{s1}(i_{bp3}+i_{cp2})\\ N_{p0}\cdot i_{sb}+N_{p1}(i_{bp1}+i_{bp4})+N_{p2}(i_{bp2}+i_{bp3})=N_{s3}(i_{cp4}+i_{ap1})+N_{s1}(i_{cp3}+i_{ap2})\\ N_{p0}\cdot i_{sc}+N_{p1}(i_{cp1}+i_{cp4})+N_{p2}(i_{cp2}+i_{cp3})=N_{s3}(i_{ap4}+i_{bp1})+N_{s1}(i_{ap3}+i_{bp2})\end{cases} \tag{6}$$

According to Kirchhoff's current law:

$$\begin{cases}i_{sa}=i_a+i_{ap1}-i_{cp4} & i_{sb}=i_b+i_{bp1}-i_{ap4} & i_{sc}=i_c+i_{cp1}-i_{bp4}\\ i_{ap2}=i_{ap1}-i_{a1} & i_{bp2}=i_{bp1}-i_{b1} & i_{cp2}=i_{cp1}-i_{c1}\\ i_{ap3}=i_{ap2}-i_{a2} & i_{bp3}=i_{bp2}-i_{b2} & i_{cp3}=i_{cp2}-i_{c2}\\ i_{ap4}=i_{ap3}-i_{a3} & i_{bp4}=i_{bp3}-i_{b3} & i_{cp4}=i_{cp3}-i_{c3}\end{cases} \tag{7}$$

Let $i_1=\begin{bmatrix}i_{ap4} & i_{bp4} & i_{cp4}\end{bmatrix}^T$ and:

$i_2=\begin{bmatrix}i_a & i_{a1} & i_{a2} & i_{a3} & i_b & i_{b1} & i_{b2} & i_{b3} & i_c & i_{c1} & i_{c2} & i_{c3}\end{bmatrix}^T$,

Then the winding currents can be calculated by Eq. (6) and Eq. (7):

$$Ai_1 = Bi_2 \tag{8}$$

In Eq. (8), matrix A is:

$$\begin{bmatrix} N_{p0}+2N_{p1}+2N_{p2} & -N_{s1}-N_{s3} & -N_{p0}-N_{s1}-N_{s3} \\ -N_{p0}-N_{s1}-N_{s3} & N_{p0}+2N_{p1}+2N_{p2} & -N_{s1}-N_{s3} \\ -N_{s1}-N_{s3} & -N_{p0}-N_{s1}-N_{s3} & N_{p0}+2N_{p1}+2N_{p2} \end{bmatrix}$$

Matrix B is:

$$\begin{bmatrix} -N_{p0} & 0 & 0 \\ -N_{p0}-N_{p1} & N_{s3} & 0 \\ -N_{p0}-N_{p1}-N_{p2} & N_{s1}+N_{s3} & 0 \\ -N_{p0}-N_{p1}-2N_{p2} & N_{s1}+N_{s3} & N_{s1} \\ 0 & -N_{p0} & 0 \\ 0 & -N_{p0}-N_{p1} & N_{s3} \\ 0 & -N_{p0}-N_{p1}-N_{p2} & N_{s1}+N_{s3} \\ N_{s1} & -N_{p0}-N_{p1}-2N_{p2} & N_{s1}+N_{s3} \\ 0 & 0 & -N_{p0} \\ N_{s3} & 0 & -N_{p0}-N_{p1} \\ N_{s1}+N_{s3} & 0 & -N_{p0}-N_{p1}-N_{p2} \\ N_{s1}+N_{s3} & N_{s1} & -N_{p0}-N_{p1}-2N_{p2} \end{bmatrix}^T$$

According to these equations and the relationship of the node currents, the currents through the autotransformer windings can be calculated concretely. In the same way, the winding currents in case of a voltage step-up can also be obtained by this analysis method.

B. Kilovolt-Ampere Rating Analysis

The formula to calculate the equivalent capacity of the autotransformer is:

$$Pdtr = 0.5\sum(Vrms \times Irms) \tag{9}$$

In this formula, V_{rms} is the effective value of each winding voltage, and I_{rms} is the effective value of each winding current.

Take $k_u = 0.8$ as an example to calculate the equivalent capacity. Then the following ratio can be obtained by Eq. (3).

$$\frac{N_{p1}}{N_{p0}} = \frac{1}{0.893} \tag{10}$$

According to the turns ratio of the autotransformer windings, the following values are used in the calculation:

$$\begin{cases} N_{p0} = 0.283 \\ N_{p1} = N_{p4} = 0.317 \\ N_{p2} = N_{p3} = 0.414 \\ N_{s1} = N_{s2} = 0.068 \\ N_{s3} = N_{s4} = 0.2 \end{cases} \tag{11}$$

Thus, matrix A is:

$$\begin{bmatrix} 1.745 & -0.268 & -0.551 \\ -0.551 & 1.745 & -0.268 \\ -0.268 & -0.551 & 1.745 \end{bmatrix}$$

Matrix B is:

$$\begin{bmatrix} -0.283 & -0.6 & -1.014 & -1.428 & 0 & 0 & 0 & 0.068 & 0 & 0.2 & 0.268 & 0.268 \\ 0 & 0.2 & 0.268 & 0.268 & -0.283 & -0.6 & -1.014 & -1.428 & 0 & 0 & 0 & 0.068 \\ 0 & 0 & 0 & 0.068 & 0 & 0.2 & 0.268 & 0.268 & -0.283 & -0.6 & -1.014 & -1.428 \end{bmatrix}$$

Therefore, the A-phase input current can be obtained by:

$$\begin{aligned} i_{sa} &= 0.8618i_a + 0.695i_{a1} + 0.4887i_{a2} + 0.2575i_{a3} + 0.01703i_b \\ &\quad - 0.04951i_{b1} - 0.05371i_{b2} + 0.004417i_{b3} + 0.1212i_c + 0.3545i_{c1} \\ &\quad + 0.565i_{c2} + 0.7381i_{c3} \end{aligned} \tag{12}$$

Similarly, the A-phase winding currents i_{ap1}, i_{ap2}, i_{ap3} and i_{ap4} can also be obtained by superposition of the transformer output currents. Then according to the relationship between transformer output currents and ATRU output current I_d, the effective values of winding currents can be calculated.

$$\begin{cases} I_{sa} = 0.6515I_d \\ I_{ap1} = 0.2566I_d \\ I_{ap2} = 0.1788I_d \\ I_{ap3} = 0.2049I_d \\ I_{ap4} = 0.3086I_d \end{cases} \tag{13}$$

The effective values of the winding voltages can be calculated by the turns ratio of the windings and Eq. (5).

$$\begin{cases} V_{Aa} = 0.1158V_d \\ V_{aap1} = 0.0818V_d \\ V_{ap1a1} = 0.1297V_d \\ V_{a1ap2} = 0.1694V_d \\ V_{ap2a2} = 0.0278V_d \end{cases} \tag{14}$$

Due to symmetry, the winding voltage values and winding current values of the other two phases are equal to the corresponding values of A phase. Therefore, the equivalent capacity of the transformer can be calculated as:

$$P_{dtr} = 0.5\sum V_{rms} \times I_{rms} = 0.4052U_dI_d \tag{15}$$

The kilovolt-ampere rating is the ratio of P_{dtr} and U_dI_d. Therefore, in case of $k_u = 0.8$, the kilovolt-ampere rating is 40.52%. Similarly, the kilovolt-ampere ratings under other voltage ratios can also be calculated.

According to the analysis and calculation, the kilovolt-ampere ratings under different values of k_u are listed in Table I. This shows that the more the output voltage changes, the more the turns of the extending winding are needed. In addition, the corresponding kilovolt-ampere rating is higher. In the case of k_u=0.2, the kilovolt-ampere rating is close to 1. In order to ensure the advantage of the ATRU in terms of volume weight, the recommended range of k_u is $k_u \in (0.2, 1.6)$.

The theoretical kilovolt-ampere rating is 0.283 in case of $k_u = 1$, which has no advantage when compared with the existing 24-pulse ATRU. However, omitting the interphase reactors can considerably reduce the complexity and volume weight of the ATRU, which provides the new structure with remarkable advantages.

TABLE I
KILOVOLT-AMPERE RATING VERSUS K_U

k_u	Kilovolt-ampere rating
0.2	0.926
0.4	0.745
0.6	0.567
0.8	0.405
1.0	0.283
1.2	0.451
1.4	0.675
1.6	0.948

V. SIMULATION AND EXPERIMENT

A. Simulation of a 24-Pulse ATRU

In Matlab/Simulink, a 24-pulse ATRU is modeled and simulated, and the input three-phase voltage is 115V/400Hz. The following current and voltage waveforms of the ATRU are recorded in the case of $k_u = 0.8$.

A-phase input voltage waveforms of the rectifier bridges are shown in Fig. 7. As shown in the diagram, the A-phase input voltage amplitude of the main bridge is about 130V, while the A-phase input voltage amplitudes of the three auxiliary bridges are 104V, 95V and 104V, respectively. In addition, the phase angles of the auxiliary bridge voltages relative to the main bridge voltage are about $26°$, $60°$ and $91°$, respectively.

The four current waveforms shown in Fig. 8 correspond to i_a (A-phase input current of the main bridge), i_{a1}, i_{a2} and i_{a3} (A-phase input currents of the three auxiliary bridges) in Fig. 1(b). This shows that each of the diodes in the main rectifier bridge is turned on for about 75° in one cycle and that each of the diodes in the auxiliary rectifier bridges is turned on for 15° in one cycle.

The mean value of the output voltage of the ATRU shown in Fig. 9 is about 224.3V, while the theoretical value of the output voltage calculated by Eq. (5) is 225V. The deviation between the two values is within the accepted range.

The voltages and currents of the A-phase windings are shown in Fig. 10. To validate the theoretical kilovolt-ampere rating in Table I, adjust k_u from 0.2 to 1.6 and record the simulation values of the winding voltages and currents. Due to limitations on space, Table II only lists three sets of data of A phase ($k_u = 0.8$, $k_u = 1$, $k_u = 1.2$). The data of the other two phases are almost equal to them. Then the corresponding kilovolt-ampere ratings can be calculated by Eq. (9). They are 0.409, 0.282 and 0.468 respectively. All of them are basically consistent with the theoretical values in Table I.

The THD of the AC input current can measure the input performance of the ATRU. Simulation values of the THD of the input current under different voltage ratios are recorded in

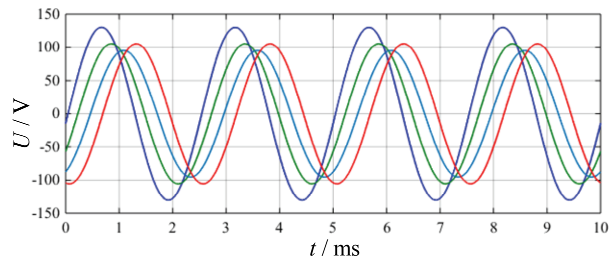

Fig. 7. Simulation waveforms of the input voltages of the rectifier bridges (A phase, $k_u = 0.8$).

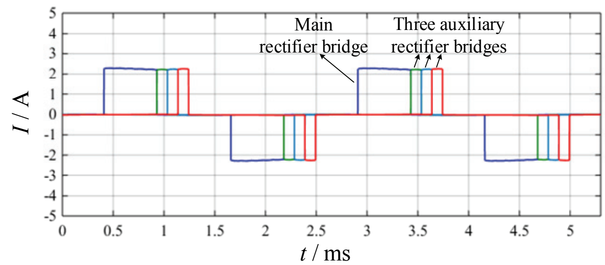

Fig. 8. Simulation waveforms of the input currents of the rectifier bridges (A phase, $k_u = 0.8$).

TABLE II
SIMULATION VALUES OF THE WINDING VOLTAGES AND CURRENTS (A PHASE)

	U/V (k_u=0.8)	I/A (k_u=0.8)	U/V (k_u=1)	I/A (k_u=1)	U/V (k_u=1.2)	I/A (k_u=1.2)
extending	25.58	1.566	—	—	27.27	3.564
$a_{p1}a_1$	28.95	0.5504	36.21	0.8064	43.44	1.264
a_1a_{p2}	37.80	0.3798	47.28	0.4874	56.74	0.8496
$a_{p3}a_3$	37.80	0.4559	47.28	0.4616	56.73	0.6592
a_3a_{p4}	28.95	0.7511	36.20	0.8436	43.43	0.9833
$b_{p3}b_2$	6.224	0.4421	7.765	0.4451	9.336	0.6504
c_2c_{p2}	6.224	0.3690	7.765	0.4730	9.335	0.8418
$c_{p1}c$	18.26	0.5313	22.84	0.7812	27.40	1.238
cb_{p4}	18.26	0.7262	22.83	0.8122	27.40	0.9537
output	224.3	2.243	280.7	2.807	336.9	3.369

TABLE III
SIMULATION VALUES OF THE INPUT CURRENT THD VERSUS K_U

k_u	THD / %
0.2	6.58
0.4	6.81
0.6	6.72
0.8	6.82
1.0	6.82
1.2	6.89
1.4	6.89
1.6	6.70

Table III. As can be seen from Table III, adding extending windings does not increase the THD of the input current. In addition, when compared with existing 24-pulse ATRUs, the THD of the new ATRU input current is desirable.

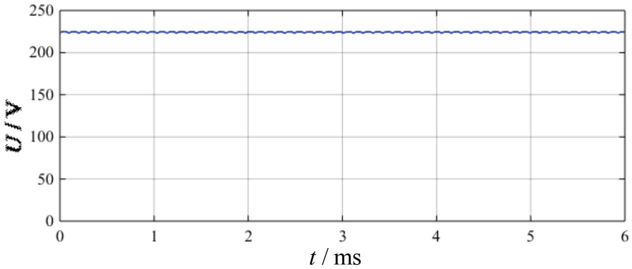

Fig. 9. Simulation waveform of the ATRU output DC voltage ($k_u = 0.8$).

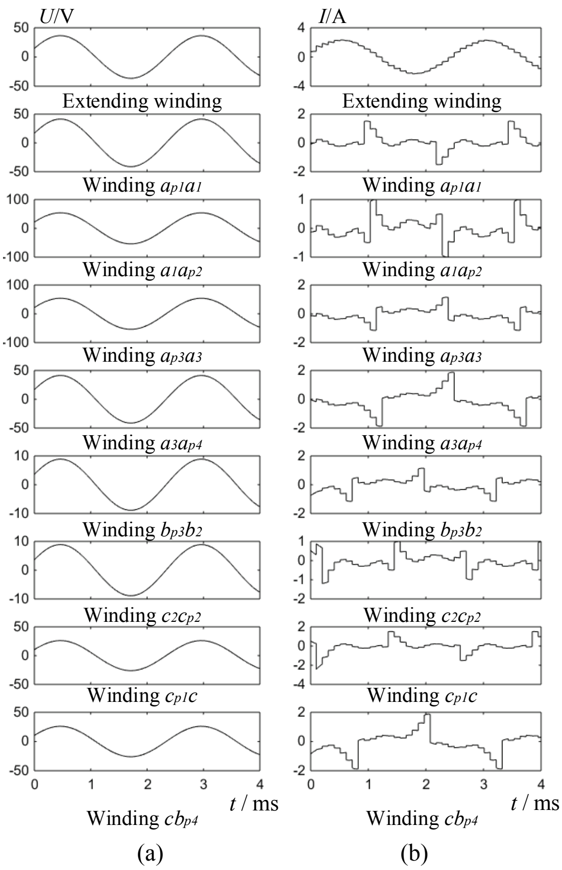

Fig. 10. Simulation waveforms of the winding voltages and currents (A phase, $k_u = 0.8$).

B. Experiment of a 24-Pulse ATRU

A step-down asymmetric 24-pulse ATRU prototype ($k_u = 0.8$), shown in Fig. 11, was fabricated and tested.

Fig. 12 shows output voltage waveforms of the transformer of the ATRU, where the input voltage amplitudes of the main and auxiliary rectifier bridges are about 130V, 101V, 95V and 101V, and the phase shift angles are about 27°, 59° and 90°, respectively. Fig. 13 shows the A-phase input currents of the four rectifier bridges. The turn-on times for each of the diodes in main bridge are about 0.53ms and the turn-on times for each of the diodes in auxiliary bridges are about 0.12ms, which converted to electric angles are 76.32° and 17.28°. Therefore, the conduction rules of the diodes and the feasibility of the bridges' parallel operation can be verified.

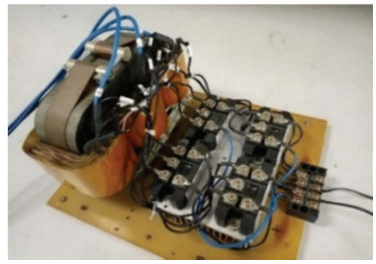

Fig. 11. Picture of the step-down 24-pulse ATRU prototype.

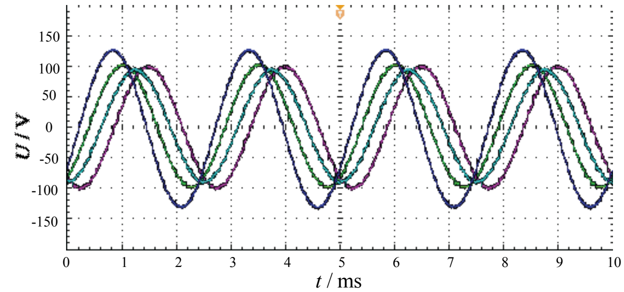

Fig. 12. Experimental waveforms of the input voltages of the rectifier bridges (A phase, $k_u = 0.8$).

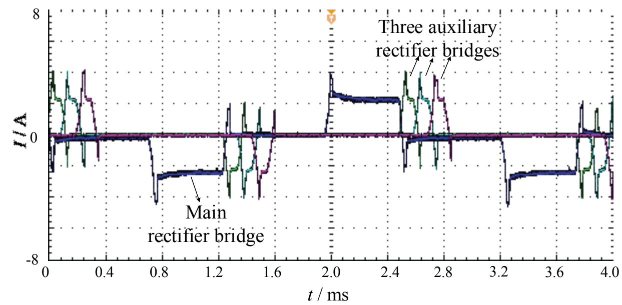

Fig. 13. Experimental waveforms of the input currents of the rectifier bridges (A phase, $k_u = 0.8$).

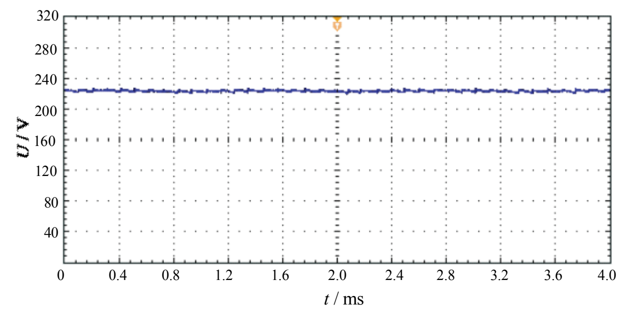

Fig. 14. Experimental waveform of the ATRU output DC voltage ($k_u = 0.8$).

Fig. 14 shows the output DC voltage whose average value is about 223V. This demonstrates that the structure can achieve a desirable regulation of the voltage. Moreover, the output DC voltage waveform is smooth enough without a filter capacitor, which indicates the good output performance of the 24-pulse ATRU prototype.

TABLE IV
EXPERIMENTAL VALUES OF THE WINDING VOLTAGES AND CURRENTS (A PHASE, K_U=0.8)

	U/V	I/A
Extending	25.37	1.54
$a_{p1}a_1$	28.52	0.55
a_1a_{p2}	37.75	0.38
$a_{p3}a_3$	37.61	0.45
a_3a_{p4}	28.90	0.75
$b_{p3}b_2$	6.37	0.42
c_2c_{p2}	6.31	0.42
$c_{p1}c$	18.05	0.55
cb_{p4}	18.34	0.75
output	223.21	2.23

To verify the theoretical kilovolt-ampere rating, experimental values of the A-phase winding voltages and currents are recorded in Table IV, and the kilovolt-ampere rating can be calculated by Eq. (9). The experimental kilovolt-ampere rating is 0.412, which is basically consistent with the theoretical and simulation values.

VI. CONCLUSIONS

A step-up and step-down asymmetrical P-topology 24-pulse ATRU is proposed in this paper.

The working principle of the new asymmetrical 24-pulse ATRU is introduced, and the turns ratio of the windings, winding currents and winding voltages are deduced. The interphase reactors required for traditional ATRUs can be omitted, which effectively reduces the volume and weight. It also improves the reliability and maintainability.

A method of adding extending windings to realize voltage step-up and step-down is introduced. Using this method can widen the application scope of a 24-pulse ATRU and the meet different requirements for the voltage of power supplies that may be proposed in the future.

The kilovolt-ampere rating of a transformer is analyzed under $k_u = 0.8$ in detail. Further, the kilovolt-ampere rating under other voltage ratios is also calculated. Based on this, a desirable range of voltage regulation is proposed.

Simulation and experimental results of a 24-pulse ATRU with a 0.8 step-down ratio are carried out. The results are in good agreement with the theoretical analysis. Thus, the feasibility of the design is verified.

ACKNOWLEDGMENT

This paper is funded by the following fund: The National Natural Science Foundation of China (Fund number 51737006); Fundation of Graduate Innovation Center in NUAA (Fund number kfjj20170709).

REFERENCES

[1] X. W. Xie, M. Wang, and F. H. Zhang, "12-pulse auto-transformer rectifier unit with current harmonic injection," *Power Electron*, Vol. 45, No. 11, pp. 9-11, Nov. 2011.

[2] F. Jiang, H. J. Ge, X. X. Dong, and L. Zhang, "Research on a new 12-pulse step-up and step-down aviation auto-transformer rectifier," *J. Power Electron.*, Vol. 18, No. 1, pp. 266-276, Jan. 2018.

[3] Z. X. Reng, "Research on multi-pulse auto-transformer rectifier units (ATRU)," M.S. Thesis, Nanjing University of Aeronautics & Astronautics, China, 2008.

[4] L. Niu, H. J. Ge, G. Yang, and F. Jiang. "Optimal design of a new step-down 18-pulse autotransformer," *Chinese J. Eng.*, Vol. 39, No. 3, pp.456-461, 2017.

[5] N. Wang, X. Wei, "Line side harmonic current analysis in 24-pulse traction rectifier substation of city track," *Transformer*, 2003.

[6] C. Cao, "Research on a 24-pulse rectifier based on autotransformer," *Huazhong University of Science & Technology*, 2005.

[7] A. O. Monroy, H. Le-Huy, and C. Lavoie, "Modeling and simulation of a 24-pulse transformer rectifier unit for more electric aircraft power system," *Electrical Systems for Aircraft, Railway and Ship Propulsion (ESARS)*, pp. 1-5, Oct. 2012.

[8] S. Yang, F. Meng, and W. Yang, "Optimum design of interphase reactor with double-tap changer applied to multipulse diode rectifier," *IEEE Trans. Ind. Electron.*, Vol. 57, No. 9, pp. 3022-3029, Sep. 2010.

[9] X. G. Ma and L. N. Bai, "Analysis and MATLAB simulation of a new 24-pluse rectification system," *Computer Simulation*, Vol. 26, No. 5, pp.262-265, 2009.

[10] Z. H. Gao, Y. Yang, W. L. Yao, and X. B. Zhang "Study on 24-pulse auto-transformer-rectifier unit for aeronautic application," *Chinese J. Power Sources*, Vol.39, No.5, pp. 987-991, 2015.

[11] F. Meng, W. Yang, S. Yang, and L. Gao, "Active harmonic reduction for 12-pulse diode bridge rectifier at DC side with two-stage auxiliary circuit," *IEEE Trans. Ind. Informat.*, Vol. 11, No. 1, pp. 64-73, Feb. 2015.

[12] W. P. Song, X. Chen, and J. Zhao, "Research on simulation model and principle of 24-pulse transformation rectifier," *Electric Drive Automation*, 2011.

[13] R. C. Fernandes, P. da Silva Oliveira, and F. J. M. de Seixas, "A family of autoconnected transformers for 12- and 18-pulse converters – Generalization for delta and wye topologies," *IEEE Trans. Power Electron.*, Vol. 26, No. 7, pp. 2065-2078, Jul. 2011

[14] F. Meng, W. Yang, and S. Yang, "Effect of voltage transformation ratio on the kilovolt-ampere rating of delta-connected auto-transformer for 12-pulse rectifier system," *IEEE Trans. Ind. Electron.*, Vol. 60, No. 9, pp. 3579-3588, Sep. 2013

[15] L. Gao, W. M. Tong, and F. G. Meng, "12-pulse rectifier system based on a novel step-up autotransform," *Journal of Power Supply*, No. 3, pp. 23-31, May 2012

[16] R. P. Burgos, A. Uan-Zo-li, and F. Lacaux, "Analysis of new step-up and step-down 18-pulse direct asymmetric auto-transformer-rectifiers," *Fourtieth IAS Annual Meeting*, Vol. 1, pp. 145-152, 2005.

Lu Zhang was born in Jiangsu, China, in 1994. She received her B.S. degree in Aircraft Airworthiness Technology from the Nanjing University of Aeronautics and Astronautics (NUAA), Nanjing, China, in 2016, where she is presently working towards her M.S. degree in Airworthiness Technology and Management. Her current research interests include multi-pulse rectification technology and aviation power supplies.

Hong-juan Ge was born in Jiangsu, China, in 1966. She received her B.S. and M.S. degrees in Electrical Engineering from Southeast University, Nanjing, China, in 1985 and 1988, respectively. She received her Ph.D. degree in Electric Machines and Electric Apparatus from the Nanjing University of Aeronautics and Astronautics, Nanjing, China, in 2006. Her current research interests include the space-vector control of PWM, AC-AC converters, and airworthiness technology.

Fan Jiang was born in Jiangxi, China, in 1993. He received his B.S. degree in Electrical Engineering and Automation and M.S. degree in Civil Aviation Electrical Engineering from the Nanjing University of Aeronautics and Astronautics (NUAA), Nanjing, China, in 2015 and 2018. His current research interests include multi-pulse rectification technology and aviation power supplies.

Guang Yang was born in China, in 1992. He received his B.S. degree in Electrical Engineering and Automation and M.S. degree in Civil Aviation Electrical Engineering from the Nanjing University of Aeronautics and Astronautics (NUAA), Nanjing, China, in 2014 and 2017. His current research interests include matrix converter control and multi-pulse rectification technology.

Yi Lin was born in Jiangsu, China, in 1994. She received her B.S. degree in Aircraft Airworthiness Technology from the Nanjing University of Aeronautics and Astronautics (NUAA), Nanjing, China, in 2016, where she is presently working towards her M.S. degree in Airworthiness Technology and Management. Her current research interests include multi-pulse rectification technology and power system reliability.