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A New 24-pulse Rectifier Transformer with Delta-extended Connection

A New 24-pulse Rectifier Transformer with Delta-extended Connection

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Abstract. The low-voltage distribution system is influenced by ever-increasing harmonics caused by nonlinear loads. A simple and reliable 24-pulse rectifier transformer for high-current and low-voltage is proposed in this paper. The proposed 24-pulse rectifier transformer consists of four secondary windings in which an original delta-extended connection is adopted. First, the existing 24-pulse rectifier system is analyzed. Second, the topology, the phase-shifting principle, the input current and the output voltage of 24-pulse transformer are described. Finally, the simulation results validate the theoretical analysis and the advantages of the new 24-pulse rectifier transformer in multi-pulse rectifier areas.

1. Introduction

To support the sustainable development of China's economy, the power industry will promote the implementation of energy saving and consumption reduction policies further [1]-[3]. The rapid development of rail transit has brought great convenience to people's travelling. However, with various kinds of electronic-based equipment widely used, a lot of harmonics have been produced and results in high value of total harmonics distortion (THD) for voltage and current in utility grid, which lowers the power quality of the rail transit power supply system and does serious harm to the traction power grid, electric distributions and electrical equipment, etc. These issues above can be suppressed to an appropriate level by using multi-pulse inverter as a multi-level inverter has the features of lower voltage stress, harmonics distortion. Multi-pulse rectifying technology is an effective way to suppress system harmonics. The more the phase number of rectifier system, the less ripple factor and total harmonic distortion will be [4]. Traditional 24-pulse rectifier transformer uses two 12-pulse phase-shifting rectifier transformers to form a 24-pulse rectifier to eliminate most of the harmonics on grid side, as shown in Figure 1. Nevertheless, the occupancy of two transformers is large and then affects the layout of other equipment in the system.

Considering the physical size of available space in prefabricated substations is limited [5], a new 24-pulse rectifier transformer can realize special phase-shifting angle by using a delta-extended connection, which not only can improve the efficiency but also reduce the space of the area greatly. In this paper, a multi-pulse rectifier transformer is applied in the utility grid, which provides reliable DC-supplies and solve the issues of high current harmonics at the utility grid. The simulation case is used to validate the proposed rectifier transformer.

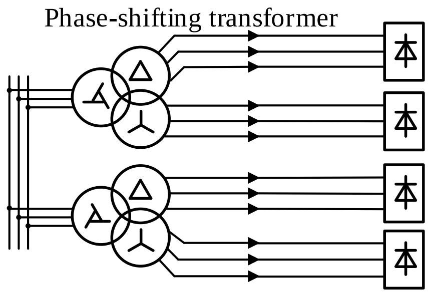
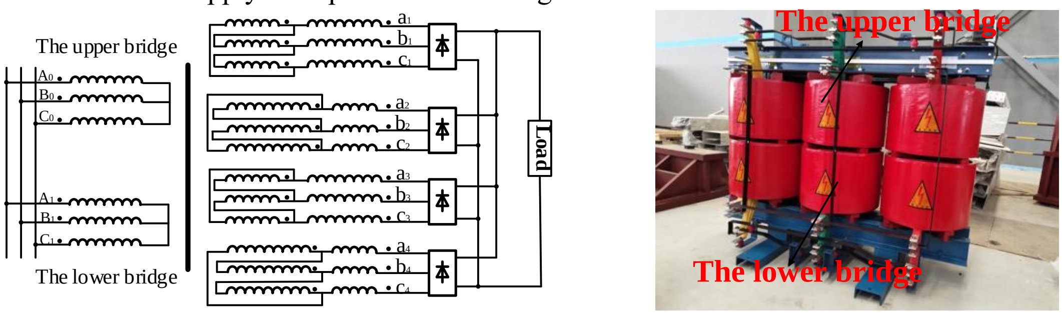


Figure 1. Traditional 24-pulse Rectifier Transformer

2. Topology

The windings of 24-pulse transformer are divided into two kinds of bridge structures with equal capacity. The upper and the lower bridge are both connected by a high voltage (HV) winding to two low voltage (LV) windings. The 24-pulse transformer with upper bridge is configured as wye/delta-extended/delta-extended and the other is configured as wye/delta-extended/delta-extended [6]. Figure 2 is the illustration of the proposed transformer. The two HV windings are connected in parallel with the same structure, wye connection. The LV windings are connected to three phase diode bridge and are composed of two sub-windings, basic winding and phase-shifting winding in delta-extended connection. LV windings are connected in equal capacity and output the same line voltage. As Figure 2 (a) shows that the phase-shifting angels of upper LV windings are +22.5º and -7.5º, therefore the phase-shifting angels of the others are -22.5º and +7.5º. The upper bridge can form a 12-pulse rectifier system, so does the lower one. However, there exists 15º difference between the two which leads to pulse 24 times in DC-supply after parallel connecting.



(a) (b)

Figure 2. Illustration of the proposed transformer
(a) structure diagram. (b) fabricated prototype

Reference [7] gives the phase-shifting principle based on delta-extended connection . As there exists an natural phasic difference between wye and delta connections, 30°. The basic winding of upper LV winding (LV1) is 30-degree ahead of HV winding (HV0), and delta-extended connection causes phase to shift -7.5°, so the ultimate result is the phase of LV1 outstrips the corresponding HV0 22.5°; the basic winding of LV2 is a 30-degree lag of HV0, and delta-extended connection causes phase to shift +22.5°, so the ultimate result is the phase of LV2 lags HV0 7.5°; the basic winding of LV3 is 30-degree lag of the corresponding HV winding (HV1), and delta-extended connection causes phase to shift +7.5°, so the ultimate result is the phase of LV3 is lag of HV1 22.5°; the basic winding of LV4 is a 30-degree lag of HV1, and delta-extended connection causes phase to shift -22.5°, so the ultimate result is the phase of LV4 outstrips HV1 7.5°.

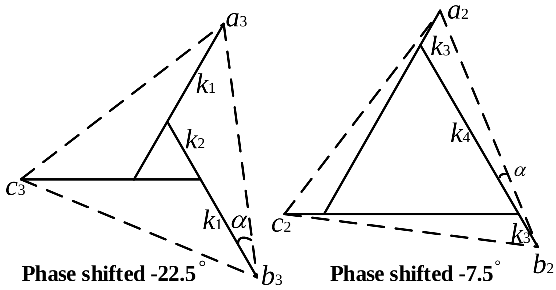


Figure 3. Vector diagram of delta-extended connection

Reference [7] gives the calculation method of turn numbers based on delta-extended connection. It is assumed that the output voltage of phase-shifting winding is 1, k_1 and k_2 are phase voltage of delta-extended winding and basic winding for phase shifted ±22.5° respectively; similarly, k_3 and k_4 are phase voltage of delta-extended winding and basic winding for phase shifted ±7.5°. Figure 3 is the vector diagram of delta-extended connection.

It is assumed that the output line voltage is 1, so according to the triangle sine laws:

$$\frac{1}{\sin 2\pi/3} = \frac{k_1}{\sin\alpha} = \frac{k_1 + k_2}{\sin(\pi/3 - \alpha)} \tag{1}$$

Equation (1) is for phase shifted ±22.5°, k_1=0.442, k_2=0.261. In like manner for phase shifted ±7.5°, k_3=0.151, k_4=0.765.

3. Operational characteristics

3.1 Analysis of input current

Assuming the default current direction is from left to right in LV windings. Marked three phase current of LV1 as $\boldsymbol{I}_{11}$, $\boldsymbol{I}_{12}$ and $\boldsymbol{I}_{13}$; likewise, for LV2, marked $\boldsymbol{I}_{11}$, $\boldsymbol{I}_{12}$ and $\boldsymbol{I}_{13}$ as current of basic winding and $\boldsymbol{I}_{a1}$, $\boldsymbol{I}_{b1}$ and $\boldsymbol{I}_{c1}$ as current of delta-extended winding. LV3, $\boldsymbol{I}_{31}$, $\boldsymbol{I}_{32}$ and $\mathbf{I}_{33}$ for basic winding, $\boldsymbol{I}_{a3}$, $\boldsymbol{I}_{b3}$ and $\boldsymbol{I}_{c3}$ for delta-extended winding. LV4, $\boldsymbol{I}_{41}$, $\boldsymbol{I}_{42}$ and $\mathbf{I}_{43}$ for basic winding, $\boldsymbol{I}_{a4}$, $\boldsymbol{I}_{b4}$ and $\boldsymbol{I}_{c4}$ for delta-extended winding. Assuming the default current direction is from right to left in HV windings. The current of HV0 is $\boldsymbol{I}_{A0}$, $\boldsymbol{I}_{B0}$ and $\boldsymbol{I}_{C0}$, and the current of HV1 is $\boldsymbol{I}_{A1}$, $\boldsymbol{I}_{B1}$ and $\boldsymbol{I}_{C1}$. Taking phase A as an example, according to Magnetic Potential Balance Principle, we can get the following results:

$$\begin{aligned} k\boldsymbol{I}'_{A0} &= \boldsymbol{I}_{11}k_2 + \boldsymbol{I}_{a1}k_1 \quad & k\boldsymbol{I}''_{A0} &= \boldsymbol{I}_{21}k_4 + \boldsymbol{I}_{a2}k_3 \\ k\boldsymbol{I}'_{A1} &= \boldsymbol{I}_{31}k_2 + \boldsymbol{I}_{a3}k_1 \quad & k\boldsymbol{I}''_{A1} &= \boldsymbol{I}_{41}k_4 + \boldsymbol{I}_{a4}k_3 \end{aligned} \tag{2}$$

And k is the turn ratio. From Figure 2 (a), the current relationship can also be caught as follows:

$$\begin{aligned} \boldsymbol{I}_{a1} &= \boldsymbol{I}_{11} - \boldsymbol{I}_{12} \quad & \boldsymbol{I}_{a2} &= \boldsymbol{I}_{21} - \boldsymbol{I}_{23} \\ \boldsymbol{I}_{a3} &= \boldsymbol{I}_{31} - \boldsymbol{I}_{33} \quad & \boldsymbol{I}_{a4} &= \boldsymbol{I}_{41} - \boldsymbol{I}_{42} \end{aligned} \tag{3}$$

Equation (3) points out the relationship between basic current and delta-extended current. That is, when the three phase basic winding is in balanced connection, the output three phase line current ($\boldsymbol{I}_a$, $\boldsymbol{I}_b$, $\boldsymbol{I}_c$) is distributed symmetrically without considering the turn numbers of delta-extended windings, and the phase is lagging behind 120° in turn. From Figure 2 (a), we can get the following results, for delta-extended current of phase A:

$$\begin{aligned} \boldsymbol{I}_{a1} &= \sum_{n=1,3,5...}^{\infty} [\frac{4\boldsymbol{I}_d}{n\pi}\cos(n\pi/6)]\sin n(\omega t + \pi/8) \quad & \boldsymbol{I}_{a2} &= \sum_{n=1,3,5...}^{\infty} [\frac{4\boldsymbol{I}_d}{n\pi}\cos(n\pi/6)]\sin n(\omega \mathrm{t} - \pi/24) \\ \boldsymbol{I}_{a3} &= \sum_{n=1,3,5...}^{\infty} [\frac{4\boldsymbol{I}_d}{n\pi}\cos(n\pi/6)]\sin n(\omega \mathrm{t} - \pi/8) \quad & \boldsymbol{I}_{a4} &= \sum_{n=1,3,5...}^{\infty} [\frac{4\boldsymbol{I}_d}{n\pi}\cos(n\pi/6)]\sin n(\omega \mathrm{t} + \pi/24) \end{aligned} \tag{4}$$

For basic current of phase A:

$$
\begin{aligned}
\boldsymbol{I}_{11} &= \frac{2}{\pi} I_d[\sin(\omega t-\frac{\pi}{24})-\frac{1}{5}\sin(5\omega t+\frac{19\pi}{24})-\frac{1}{7}\sin(7\omega t+\frac{17\pi}{24})+\frac{1}{11}\sin(11\omega t+\frac{37\pi}{24})+\frac{1}{13}\sin(13\omega t+\frac{35\pi}{24})-...]\\
\boldsymbol{I}_{21} &= \frac{2}{\pi} I_d[\sin(\omega t+\frac{\pi}{8})-\frac{1}{5}\sin(5\omega t-\frac{3\pi}{8})-\frac{1}{7}\sin(7\omega t-\frac{\pi}{8})+\frac{1}{11}\sin(11\omega t-\frac{5\pi}{8})+\frac{1}{13}\sin(13\omega t-\frac{3\pi}{8})-...]\\
\boldsymbol{I}_{31} &= \frac{2}{\pi} I_d[\sin(\omega t+\frac{\pi}{24})-\frac{1}{5}\sin(5\omega t-\frac{19\pi}{24})-\frac{1}{7}\sin(7\omega t-\frac{25\pi}{24})+\frac{1}{11}\sin(11\omega t+\frac{11\pi}{24})+\frac{1}{13}\sin(13\omega t+\frac{13\pi}{24})-...]\\
\boldsymbol{I}_{41} &= \frac{2}{\pi} I_d[\sin(\omega t-\frac{\pi}{8})-\frac{1}{5}\sin(5\omega t+\frac{3\pi}{8})-\frac{1}{7}\sin(7\omega t+\frac{\pi}{8})+\frac{1}{11}\sin(11\omega t+\frac{5\pi}{8})+\frac{1}{13}\sin(13\omega t+\frac{3\pi}{8})-...]
\end{aligned} \tag{5}
$$

The HV windings are connected in parallel, so the input current at the grid side is satisfied the following equation:

$$
\begin{aligned}
\boldsymbol{I}_A = \boldsymbol{I}_{A0} + \boldsymbol{I}_{A1} &= (\boldsymbol{I}_{11}k_2 + \boldsymbol{I}_{a1}k_1 + \boldsymbol{I}_{21}k_4 + \boldsymbol{I}_{a2}k_3 + \boldsymbol{I}_{31}k + \boldsymbol{I}_{a3}k_1 + \boldsymbol{I}_{41}k_4 + \boldsymbol{I}_{a4}k_3)/k\\
&= [(\boldsymbol{I}_{a1}+\boldsymbol{I}_{a3})k_1 + (\boldsymbol{I}_{11}+\boldsymbol{I}_{31})k_2 + (\boldsymbol{I}_{a2}+\boldsymbol{I}_{a4})k_3 + (\boldsymbol{I}_{21}+\boldsymbol{I}_{41})k_4]/k
\end{aligned} \tag{6}
$$

Substituting equation (1)-(5) into equation (6), the amplitude of input harmonic current can be calculated sequentially. Take $n=6k\pm1$ ($k<4$) into equation (6), that is, the input current $\boldsymbol{I}_A$ of 24-pulse phase-shifting system does not contain $6k\pm1$ ($k<4$) harmonics. The number of harmonics contained in $\boldsymbol{I}_A$ is only $24k\pm1$ times, a minimum of 23 times. Above all, there only exist $24k\pm1$ times harmonics on the grid side current. The grid side harmonic currents are shown in Table 1.

Table 1. The amplitude and proportion of grid side harmonics

Order	Amplitude (A_n)	Proportion(A_n/A_1)	Order	Amplitude (A_n)	Proportion(A_n/A_1)
1	$4.005I_d/k$	1	17	1.8089e-05 I_d/k	0.00045166%
5	9.7151e-05 I_d/k	0.0024%	19	2.5566e-05 I_d/k	0.00063835%
7	4.3930e-05 I_d/k	0.0011%	23	0.1739 I_d/k	4.3421%
11	3.4230e-05 I_d/k	0.00085468%	25	0.1600 I_d/k	3.9950%
13	2.8964e-05 I_d/k	0.0007232%			

Table 1 indicates that the first harmonics of 24-pulse rectifier systems start at 23th and 25th. Although some low-order harmonics are still contained, their proportion are so negligible that it can be neglected compared to the 23th and 25th harmonic currents.

3.2 Analysis of output voltage

For multi-pulse rectifier technology, the quality of output voltage is one of the most important factors to measure the performance of the system, and it is also the key for the load to perform normally. The ripple factor (RF), γ, is often used to assessed the quality of DC output voltage. The calculation method for γ is given by equation (7):

$$
\gamma = \frac{V_0}{U_0} = \frac{U_m - U_0}{\sqrt{2}U_0} \tag{7}
$$

Where V_0, U_m ,U_0, are peak voltage in AC components, maximum value, average value of output voltage, respectively.

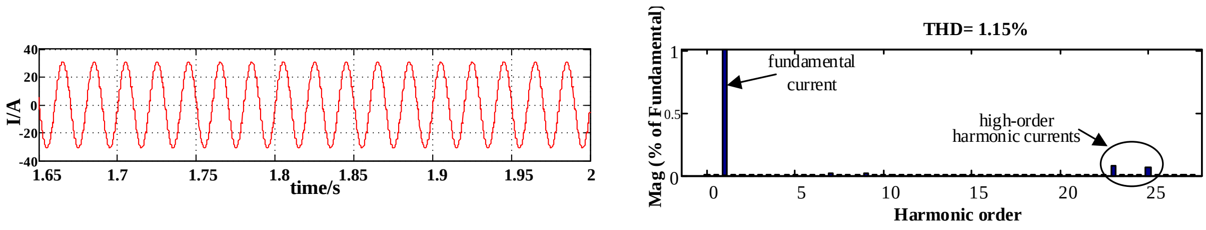
The requirements for the curve of pulsating DC which is connected to rectifiers is as straight as possible, and the smaller the pulsation, the better. The three phase AC is connected to three phase diode bridge and then exports DC sources, however, the real output DC is not consistent with the ideal DC, and usually the DC power is called pulsating DC. The output DC current after rectifying by the 24-pulse transformer is theoretically a pulsating DC with 24 pulsations in one cycle. The use of multi-phase rectifier circuit is an effective measure to suppress the ripple factor of output voltage.

4. Simulation results

The simulation model is established to verify the effectiveness of the proposed system. Some of the simulation parameters are listed in Table 2. The current waveform and spectrum of input current, $\boldsymbol{I}_{AB}$ are recorded and shown in Figure 4.

Table 2. Simulation parameters

Parameters	Grid side voltage	Secondary voltage	Transformer capacity
Value	6600V	715V	500kVA

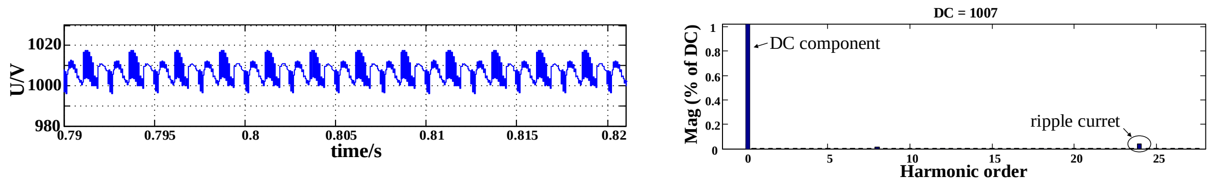


(a) (b)

Figure 4. Input current waveform and spectrum
(a) the current waveform. (b) the current spectrum

From Figure 4 we can note that there exist 23th and 25th harmonics in grid side with some low-order harmonics. However, the amplitude of these harmonics is so much smaller compared to 23th or 25th harmonics that it cannot have an effect on the large power grid which has the characteristics of large capacity and high voltage level. And for Figure 4 (a), it can be seen that the current waveform presents the awesome sine wave, and Figure 4 (b) authenticates that the current THD in grid side is decreased to 1.15% with the use of 24-pulse rectifier system.

The waveform and spectrum of output voltage, U_{dc}, are recorded and shown in Figure 5.



(a) (b)

Figure 5. Waveform and spectrum of DC voltage
(a) waveform of output voltage. (b) spectrum of output voltage

It can be seen that the waveform of output voltage pulsates 24 times in one time period, 0.02 seconds. In Figure 5(b), it sets display style related to DC component. From Figure 5 it can note the average value of output voltage is 1007V, and the average value of 24th ripple is about 0.46% of DC components, which is much smaller than DC component. From Figure 5(a), U_m=1018V, U_0=1007V, so by equation (7), the ripple factor, γ=0.77%, which meets the standard for ripple factor.

5. Conclusion

In this paper, a new 24-pulse rectifier transformer based on delta-extended connection is proposed for the first time. The phase-shifting task of traditional two transformers is highly integrated into one transformer, so the material using rate is high. The structure of the transformer can be divided into the upper and the lower bridge, there are 5 windings in each phase. Simple winding structure, good comprehensive performance, flexible designing, all these qualities can be seen in this new transformer. This new transformer not only can effectively restrain lower harmonic current on the grid side but also can improve the quality of output voltage. By analyzing total harmonic distortion of input current and ripple factor of output voltage, it draws the conclusion that this new 24-pulse rectifier transformer can meet the requirements of the urban rail transit power supply system.

Acknowledgments
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