WEP Warwick Evans Publishing

International Journal of Electric Power and Energy Studies
ISSN: 3006-2004 (Print), ISSN: 3006-0826 (Online) | Volume 2, Number 1, Year 2024
DOI: https://doi.org/10.62051/ijepes.v2n1.03
Journal homepage: https://wepub.org/index.php/IJEPES/index

# Optimized Design of New 24-pulse Rectifier

Wenbin Mu*, Hao Wu

School of Automation and Information Engineering, Sichuan University of Science and Engineering, Yibin 644000, China

## ABSTRACT

Compared with the conventional 24-pulse rectifier, the low-voltage winding of the rectifier transformer must be connected in the y and d modes, so that the voltage phase of the low-voltage side of the transformer is separated by 30° in sequence. This paper uses the phasor method to obtain a set of phase voltages that move towards 15° through the equivalent of three-phase voltages, so that the two sets of voltages produce a phase difference. Then, through decoupling and voltage reduction, the electrical quantity is converted into a signal quantity, the voltage level is reduced, and then the electrical quantity output is obtained to obtain the required voltage value. Finally, the required DC power is obtained through the rectification system. The effectiveness of the reverse model of this paper is verified by comparing the results and efficiency with the conventional 24-pulse rectifier.

## KEYWORDS

Simulink; Urban Rail Traction; Rectifier; Decoupling; Real-time Simulation.

## 1. INTRODUCTION

In recent years, China's urban rail transit has experienced rapid development, and the training of professionals in urban rail transit has been increasingly emphasized in higher education institutions. However, in the actual teaching process, there are still challenges such as unreasonable course design and shortage of local educational resources. The urban rail transit power supply system is an electrically driven vehicle transportation system, which plays a role in alleviating traffic congestion and saving electric power resources.

In recent years, some researchers have studied and analyzed the urban rail traction rectifier. Dong Haiyan et al. [3] analyzed the principle of the 24-pulse rectifier, and built a 24-pulse rectifier simulation model using the SIMULINK toolbox. The harmonic current on the grid side and the DC side were analyzed through simulation. Wang Heng et al. [4] proposed a new 24-pulse rectification method to suppress the impact of harmonics on the power system. The simulation results show the applicability of this model in rail transportation. Fang Fang et al. [5] analyzed the principle of the circular transformer applied to the 24-pulse rectifier. Based on the principle of magnetic potential balance, the harmonic components of the grid side current were studied.

Although there are many studies on the 24-pulse rectifier, there are not many studies on the 24-pulse rectifier and the comprehensive comparison of several rectification methods. Therefore, this paper uses the phasor method and decoupling in the Simulink simulation software to compare several rectification methods and verify the optimization effect of the rectifier model in this paper.

First, the phasor method is used to calculate two sets of parameters, and the voltage is equivalent to the controlled voltage source. Two sets of voltages with a phase difference of 15° are obtained, and the required voltage value is obtained after decoupling and voltage reduction. Finally, the 24-pulse DC voltage is obtained through the rectification system.

# 2. OPTIMIZED DESIGN OF 24-PULSE RECTIFIER

## 2.1. Principle of Pulse Rectifier Transformer

Nowadays, if we divide the traction transformer voltage level, China has three common levels: 10kV, 20kV, and 35kV. If we look at the rectification pulse, China has two common types: 12-pulse and equivalent 24-pulse. Currently, the most widely used in the traction power supply system of urban rail transit in various cities in China is the double-unit equivalent 24-pulse traction rectifier [6]. The transformer is the core device of the traction rectifier substation, and the wiring diagram of the unit is shown in Figure 1.

From the figure, we can see that the high-voltage side windings of the two transformers are phase-shifted by the Y-Δ connection, so that the phase difference of the line voltage of the low-voltage side windings of the two transformers is 15°. Then, after passing through the three-phase bridge rectifier circuits B1, B2, B3, B4 respectively, the DC outputs of the rectifiers are all connected, so that the voltage will fluctuate 24 times in one cycle, forming a 24-pulse rectification system.

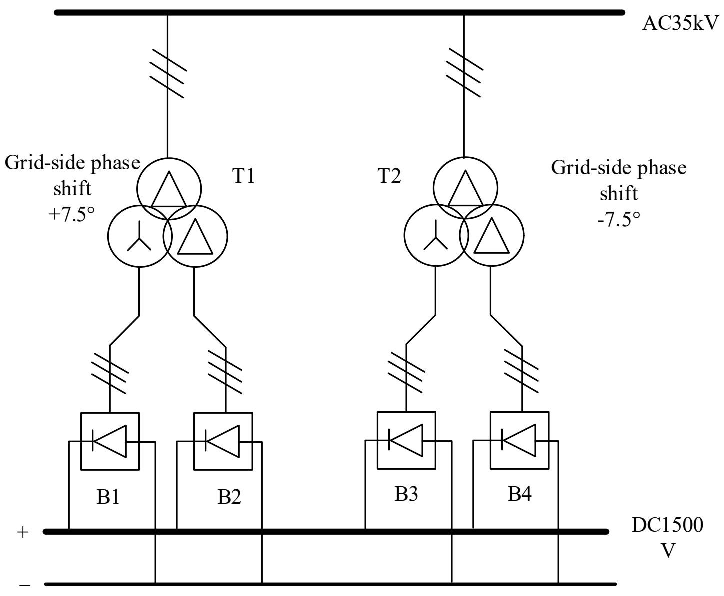


**Figure 1.** Rectifier wiring diagram

According to China's "Subway Design Code" (GB50157-2003), the load level of the traction rectifier should meet the following requirements, as shown in Table 1: translation.

**Table 1.** Rectifier Specific Parameters

| name | parameter |
|---|---|
| No-load input voltage | 35kV |
| DC output voltage at no-load | DC 1650V |
| Rated voltage at no-load | AC 1180V |
| Traction rectifier 100% rated load | Continuous |
| Traction rectifier 150% rated load | 2h |
| Traction rectifier 200% rated load | 1min |
| System voltage nominal value | 1500V |
| System voltage maximum value | 1800V |
| System voltage minimum value | 1000V |

These connection methods are Dy11d0 and Dy1d2. These connection methods are common for rectifier transformers. These connection methods determine the phase difference of the transformer and the number of direct current pulses in the output. In practical operation, two transformers (T1, T2) can be connected in parallel to form a complete rectifier. The connection method for transformer T1 is Dy11d0, and the connection method for transformer T2 is Dy1d2. The letter D in these connection methods represents the delta connection method. The connection method of the rectifier transformer is shown in Figure 2.

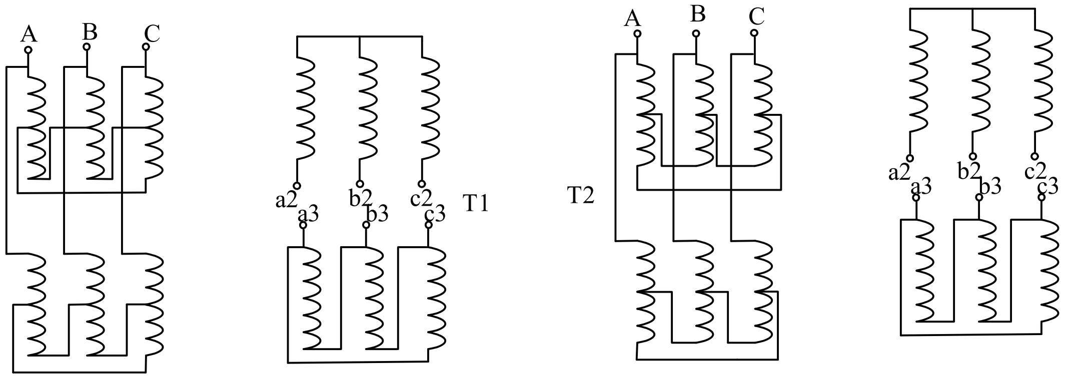


**Figure 2.** Schematic diagram of the rectifier transformer coupling junction

To obtain the same line voltage, the low-voltage winding of the rectifier transformer must be connected in the y and d connection method. In this way, the phase of the output voltage on the low-voltage side of the transformer will be 30° apart, allowing for the realization of a twelve-pulse rectification system. Additionally, if one transformer is phase-shifted by -7.5° and another is phase-shifted by +7.5°, and then the two rectifiers are connected in parallel, a twenty-four-pulse rectification system can be achieved. The phase of the output voltage on the low-voltage winding of the transformer will be 15° apart, as shown in Figure 3 of the phase diagram of the low-voltage winding of the rectifier system.

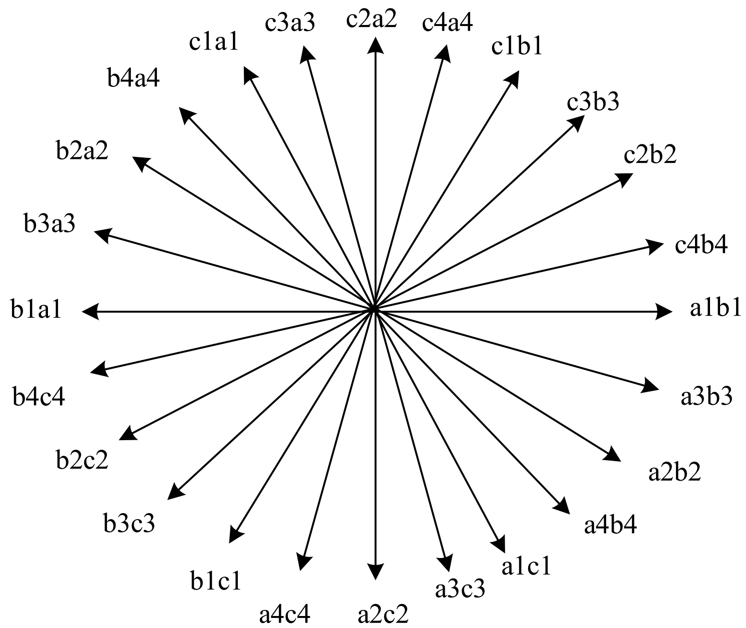


**Figure 3.** Rectifier transformer valve side voltage phasor diagram

## 2.2. Rectifier Transformer Modeling

The rectifier transformer is a special type of transformer used in DC rectification systems. It has a unique structure, reliable grounding capability, and good corrosion resistance. If you want to achieve

24 fluctuations of direct current within one cycle, it is necessary to implement a phase shift of +7.5° and -7.5° on the primary side of the rectifier. Compared to the traditional method of using the extended delta connection on the high-voltage side of the traction transformer and using the built-in phase-shifting transformer connection method in the Matlab/Simulink model library, this article uses the high-voltage side three-phase voltage source to equivalently represent the ABC three-phase voltages with controlled voltage sources, and uses two of them to equivalently produce another voltage waveform with a phase shift of +7.5°, as shown in the equivalent vector diagram in Figure 4.

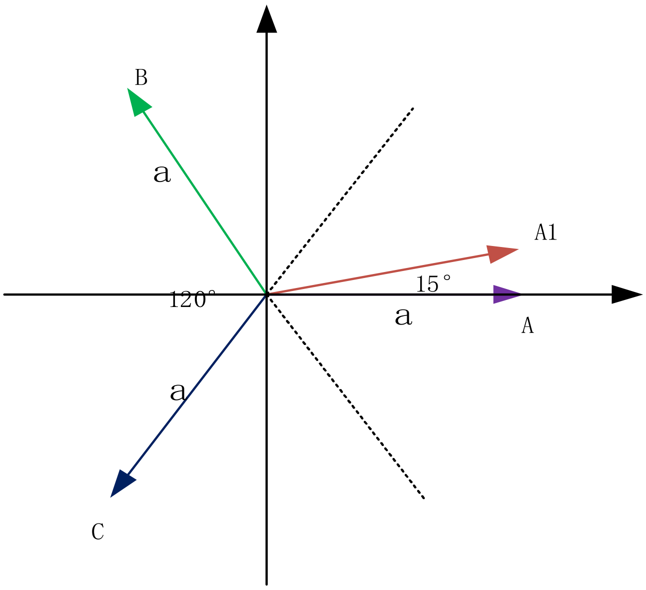


**Figure 4.** Three-phase voltage phasor diagram

The ABC three-phase voltage is expressed in the form of complex numbers as follows:

$$\begin{cases} A = a \\ B = a*(-\frac{1}{2}+\frac{\sqrt{3}}{2}j) \\ C = a*(-\frac{1}{2}-\frac{\sqrt{3}}{2}j) \\ A1 = a*(\frac{\sqrt{6}+\sqrt{2}}{4}+\frac{\sqrt{6}-\sqrt{2}}{4}j) \end{cases} \tag{1}$$

According to the phasor method and the mathematical trigonometric relationship, the relationship between phase voltage can be derived, and the derivation process of the phasor method is mainly explained here.

$$x*B + y*C = A1 \tag{2}$$

Substituting (1) into (2) where the real part is equal to the imaginary part yields the values of x and y:

$$x = -\frac{\sqrt{6}}{3}$$
$$y = \frac{3\sqrt{2} - \sqrt{6}}{6} \tag{3}$$

B phase and C phase voltages lead or lag by 15°, and similarly, it can be calculated that A1, B1, and C1, as calculated by the phasor method, all differ from the original three-phase voltages by 15°, thus achieving 24-pulse DC. Compared to traditional rectification methods, in order to obtain the same line voltage, the low-voltage winding of the rectifier transformer must be connected in the y and d manner, so that the voltage phase on the low-voltage side of the transformer is sequentially separated by 30°. Using the phasor method to derive the shift of the three-phase voltage by 30° to equivalently output the voltage on the low-voltage side of the three-winding transformer connected in the y and d manner can greatly reduce model calculation resources and improve model simulation speed.

The voltage calculated by the phasor method is equivalent to a controlled voltage source, and the equivalent model is shown in Figure 5.

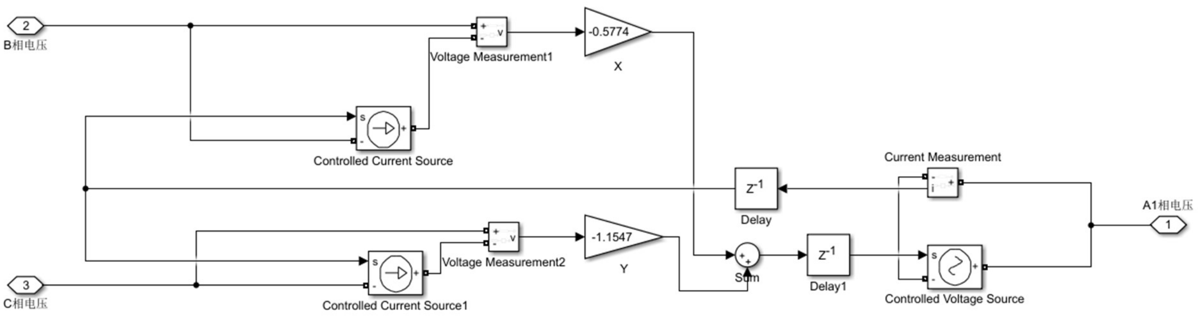


**Figure 5.** Controlled voltage source equivalence model

After shifting the voltage phase, the high-voltage voltage of 35KV is also stepped-down to a low voltage of 1180V, and the decoupling method is used to step down the controlled voltage source. The voltage signal of the controlled voltage source is multiplied by a coefficient to obtain the voltage value after the step-down, and the low-voltage side is multiplied by a value equal to the voltage value of the high-voltage side and the signal is returned to the controlled voltage source on the high-voltage side, and the decoupling structure is shown in Figure 6.

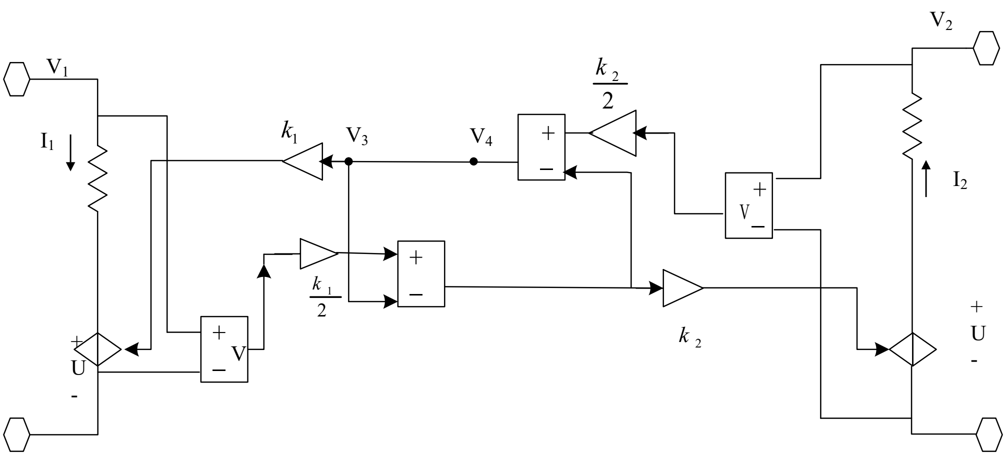


**Figure 6.** Step-down decoupling structure diagram

From the circuit principle, it can be known that:

$$V_4 = \frac{2V_2}{K_2} - (\frac{2V_1}{K_1} - V_3) \quad (4)$$

Since ③and ④ are the same signal points in the signal line, there is V3=V4, and substituting (4) can be obtained by the formula:

$$\frac{V_1}{K_1} = \frac{V_2}{K_2} \quad (5)$$

Among them, V1 is 35kV on the high-voltage side, and V2 is 1180V on the low-voltage side; So the values of K1 and K2 can be obtained; However, since the high-voltage side is the line voltage value, the value of K1 on the high-voltage side needs to be multiplied by .

### 2.3. Modeling of Rectifier Systems

The rectifier system is composed of some devices that can convert alternating current into direct current, among which the rectifier circuit can be divided into many different ways, as shown in Table 2.

**Table 2.** Classification of rectifier circuits

| Categorization | Classification of rectifier circuits |
|---|---|
| By the number of phases of the input power supply | Single-phase, three-phase, multi-phase |
| Press the rectifier circuit | Semi-controlled rectification, full-controlled rectification |
| Press Rectifier Device | Controllable, uncontrollable |
| Press the input waveform | Half-wave rectification, full-wave rectification |

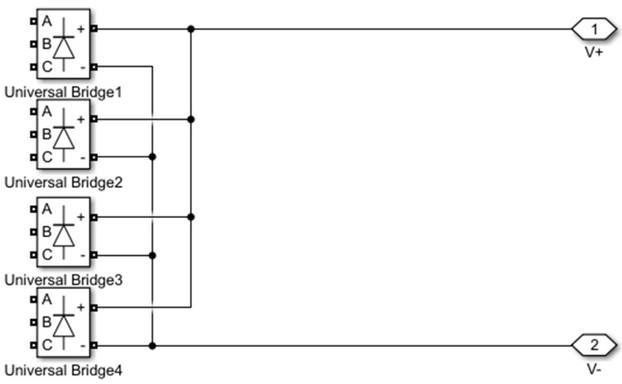


**Figure 7.** Rectifier bridge model

Because of China's special national conditions, the construction of subway cities are currently large flow of people, so the subway load must be heavy-duty load, but also to weaken the influence of harmonics as much as possible, so here this paper uses the H-phase uncontrollable rectification mode is the most appropriate, rectifier diode can be directly connected to form the rectifier circuit under the rectifier mode. There are many advantages to this method, such as the simple circuit structure and easy maneuvering, so it is easy to manage. Therefore, in order to meet the requirements of the DC traction power supply system of metro engineering, this method will also be used in the modeling of the rectifier circuit in this paper. The main rectifier circuit consists of two three-phase full-wave rectifier bridges connected in parallel, modeled using the rectifier bridge model from the Simulink component library, as shown in Figure 7.

Table 3 shows the parameter settings:

**Table 3.** Rectifier parameter settings

| name | Parameter settings |
|---|---|
| Absorption resistance | 100000Ω |
| Absorbent capacitance | 0.000001F |
| Diode forward resistance | 0.55mΩ |
| Diode forward inductance | 0 |
| Diode forward voltage | 5V |

## 3. ARITHMETIC VALIDATION

Since the transformer model and rectifier model have been built on Simulink in this paper, this paper only needs to connect the above models to complete the modeling of the 24-pulse rectifier. The model is shown in Figure 8.

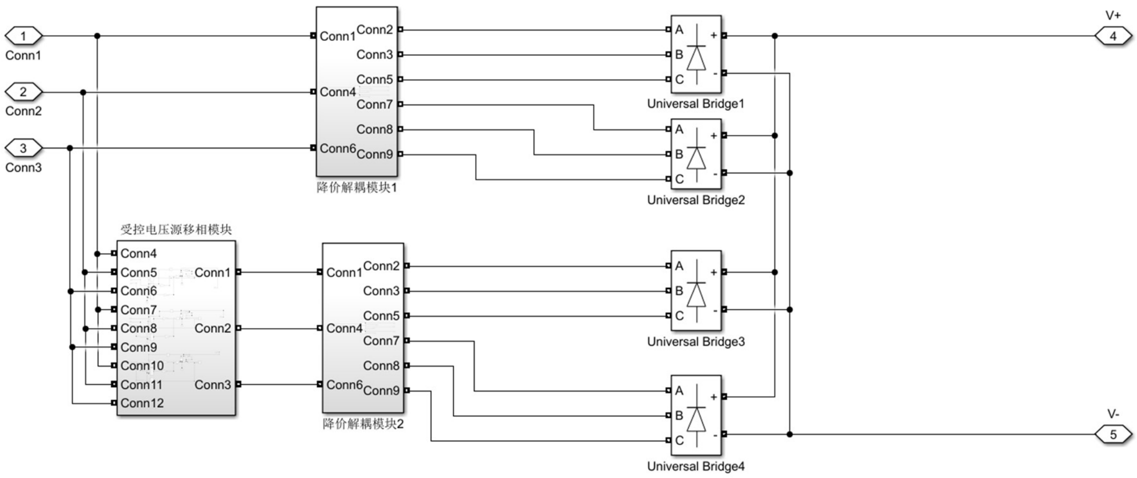


**Figure 8.** Modeling of a 24-pulse rectifier

The basic structure of the 24-pulse rectifier is shown in Figure 8. On the left is the moving module, and in the middle is the step-down module, and the two are connected together to an equivalent three-winding transformer to add a moving transformer. Compared with the conventional 24-pulse rectifier, the appeal modeling method can improve the simulation speed and reduce the subsequent real-time simulation hardware resource consumption. Figure 9 shows a comparison of the rectification effects of the two methods.

In order to compare the rectification effect of the 24-pulse wave more intuitively, the rectification on the low-voltage side of the two different rectifiers is compared to different voltages. After analysis and comparison, it can be obtained that the rectification effect of the two rectifiers is the same, and the feasibility of the rectifier model can be verified. Next, use the Speedgoat real-time simulator to put two different rectifiers into the real-time simulation machine for simulation, Speedgoat will calculate the time required for a cycle of simulation model calculation, the longer the time required for a cycle, that is, the larger the resources required for simulation, the more computing resources the model, the slower the speed of simulation. Figure 10 shows a comparison of the computing resources of two different rectifier models.

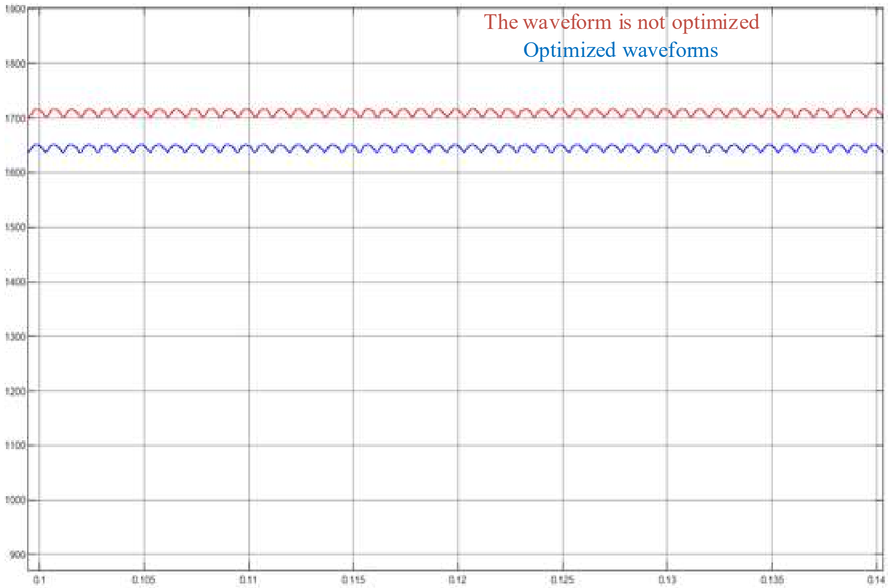


**Figure 9.** Comparison of the rectification effect of the two types of rectifiers

**Table 4.** The time required for one cycle of operation for both rectifiers

| Section | Maximum Turnaround Time in ns | Average Turnaround Time in ns | Maximum Execution Time in ns | Average Execution Time in ns | Calls |
|---|---|---|---|---|---|
| Timer Interrupt | 3068 | 824 | 3068 | 824 | 409255 |
| byq1 [5e-05 0] | 30395 | 5615 | 30395 | 5615 | 409255 |
| byq2 [5e-05 0] | 17406 | 2149 | 17406 | 2149 | 409255 |

In the figure, BYQ1 is the conventional rectifier model, and BYQ2 is the rectifier model built in this paper, and the time required for a cycle of operation is determined by the standard of the average task time of the model, because not each module is in the maximum simulation step of one cycle of operation in the process of operation, and the new rectifier model built in this paper saves 61.7% of computing resources compared with the conventional model, and the simulation speed of the model is also doubled. From the analysis of simulation results and simulation speed, the new rectifier model proposed in this paper is effective and feasible.

## 4. SUMMARY

From the experimental comparison, it can be seen that the rectification effect of the two rectification methods is the same, and the equivalent decoupling method using the phasor method to move to the controlled voltage source requires less time than the conventional shift to the transformer and the three-winding step-down device for one cycle, and the simulation speed is faster and takes up less resources. It is of great significance for the design of the future urban rail traction power supply system, and the model saves computing resources and the simulation speed is faster, which lays a foundation for the establishment of a more realistic HIL hardware-in-the-loop simulation of subway traction power supply in the future.

## CONFLICTS OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## REFERENCES

[1] Liao Aihua, Fang Yu, Shi Wei, et al. Research on Professional Course Setting Based on Cultivation of Innovation Ability-Taking Shanghai University of Engineering and Technology Urban Rail Transit Vehicle Engineering Major as an Example[J]. China Higher Education Research, 2014(Z1):59-60.

[2] Li Hongbo, Ding Rongjun, Zhang Chao, et al. Smart Traction Power Supply System for Urban Rail Transit[J]. Locomotive & Electric Car, 2021(03):1-8.

[3] Dong Haiyan, Tian Mingxing, Du Binxian, et al. Simulation and Harmonic Current Analysis of 24-Pulse Rectifier for Metro[J]. Power Supply Technology, 2011, 35(05):593-594.

[4] Wang Heng, Cui Xue, Feng Yunbin, et al. Simulation Study of 24-Pulse Autotransformer Rectifier Applied in Rail Transit[J]. Electric Measurement & Instrumentation, 2017, 54(07):1-6.

[5] Fang Fang, Wang Tiejun, Jiang Xiaoyi, et al. Harmonic Problems of New 24-Pulse Rectifier[J]. Journal of Naval University of Engineering, 2016, 28(01):7-10.

[6] Wei Guangyao. Modeling and Simulation of Metro Traction Power Supply System[D]. Southwest Jiaotong University, 2017.