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Three-Phase Bridge Fully-Controlled Rectifier Circuit Design Based On Digital Integrated Circuits

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Abstract:

This paper aims to design and analyze a three-phase fully controlled bridge rectifier circuit. The paper first introduces the basic principles and advantages of the three-phase fully controlled bridge rectifier circuit and then elaborates on five key aspects of the design: transformer design, thyristor selection, thyristor protection design, trigger circuit design, and trigger circuit power supply design. During the design process, parameters such as the motor's rated power, voltage, current, and resistance were considered to ensure that the selection of thyristor parameters and protective measures meet the needs of practical applications. In addition, the paper discusses the design of synchronous transformers, phase selection, the application of the KJ004 trigger circuit, and the design of the trigger circuit power supply. Finally, the circuit was simulated using Matlab simulation tools, the circuit design was optimized, and satisfactory pulse waveforms and output waveforms were obtained by adjusting the experimental time. The research in this paper provides theoretical basis and practical guidance for the optimized design of three-phase fully controlled bridge rectifier circuits.

Keywords: Three-phase fully controlled bridge rectifier circuit; Transformer design; Thyristor selection; Protection design; Trigger circuit;

1. Introduction

The individual phase control of three-phase converters for industrial applications uses a large number of components. The three-phase fully controlled bridge rectifier circuit is a circuit structure that converts alternating current (AC) into direct current (DC) and consists of six thyristors (SCRs), with two thyristors corresponding to each phase of alternating current, and by controlling the conduction angle of these thyristors, the size and waveform of the output DC voltage can be adjusted [1]. Its advantages include high efficiency, adjustable output voltage, low harmonic content, high power factor and good stability. And it has an advantage in the form of minimum delay of one sixth of period for the corrections of the firing angle [2]. Because the fully controlled rectifier technology can precisely control the conduction and shutdown of the thyristors, thereby reducing energy losses, three-phase fully controlled bridge rectifier circuits are widely used in DC motor drives, electroplating and electrolysis, uninterruptible power supplies (UPS), power transmission, and high-power battery charging [3]. In these applications, the output DC voltage can be easily adjusted by adjusting the triggering angle of the thyristor to meet the needs of different loads. In addition, the output voltage waveform of the three-phase rectifier circuit is smoother, with lower harmonic content and higher power factor, which is conducive to the effective use of electric energy [4]. In conclusion, three-phase fully controlled bridge rectifier circuit plays an important role in the industrial and electric power field by virtue of its high efficiency, stability, adjustability and other advantages.

So for its optimal design is crucial, this paper will start from five aspects of the design of three-phase fully controlled bridge, including the design of the transformer, thyristor selection, thyristor protection design, trigger circuit design and trigger circuit power supply design.

The article is divided into four sections. The first section is the introduction, which begins with an overview of the research background and significance of the paper. The second section focuses on circuit design, providing detailed descriptions of the design specifics across five distinct parts of the circuit. The third section pertains to Matlab simulation, elucidating the experimental methodology of utilizing Matlab's simulation capabilities to model images and derive results. The conclusion is presented in the fourth section, offering a summary of the entire paper.

2. Circuit Design

2.1 Overall Circuit Framework Diagram

Other parameters are specified in this paper for the purpose of the design of each part. The rectifier load is a 10KW DC motor, rated voltage DC 220V, rated current 55A, armature resistance 0.5Ω, total resistance 1Ω, input line voltage AC 380V (+5~-10%), output voltage DC 0~220V, maximum output current λIn (λ=1.5), minimum α-angle 15°. Confirm the connection relationship between each module to get the overall circuit framework diagram as in Figure 1

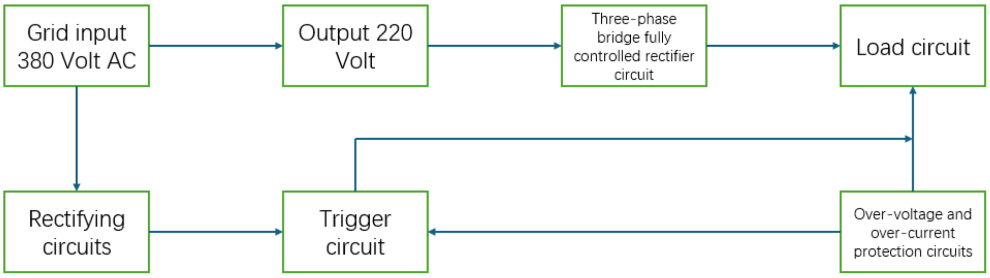

Fig. 1 Overall Circuit Framework Diagram

2.2 Transformer Designs

Transformer design includes both the design of the main transformer circuit and the calculation of the rectifier transformer parameters. The selection of the rectifier circuit should be decided according to the user's power supply and the capacity of the unit. This design uses a three-phase bridge rectifier circuit. The schematic Figure 2 shows the resistive load considering the resistive characteristic of the motor. Thyristors are divided into two groups, common cathode group and common anode group, according to the connection method. The conduction sequence is VT1-VT2-VT3-VT4-VT5-VT6, and the transformer is Y/Y12 connection.

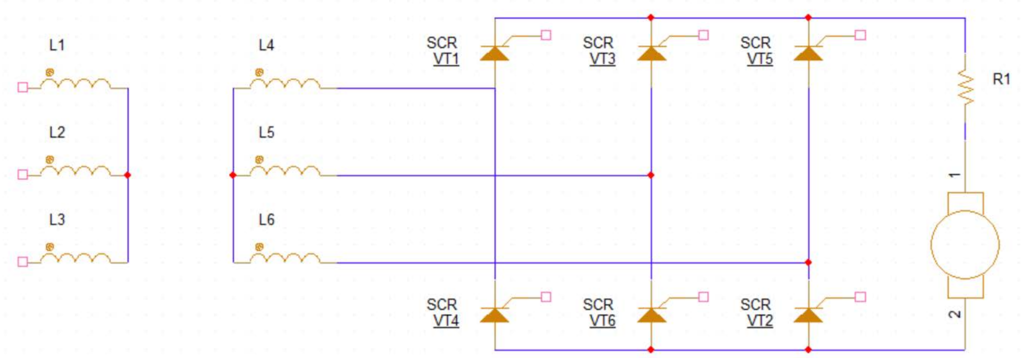

Fig. 2 Bridge Circuit Schematic

Calculating the rectifier transformer parameters, U_d is maximum 220 volts at α = 15°, so firstly get the phase voltage on the primary side of the transformer U_1 , the secondary phase voltage U_2 and the load current I_d. Then the secondary current I_2 can be calculated through the load current. Through $U_1I_1 = U_2I_2$, the primary current can be solved.

$$U_1 = \backslash raisebox1ex\$380\$/\backslash raisebox-1ex\$\sqrt{3}\$ = 220V \tag{1}$$

$$U_2 = \frac{U_d}{2.34cos\alpha} = \frac{220}{2.34cos15^0} = 97.33V \tag{2}$$

$$I_d = \lambda I_n = 1.5 \times 55 = 82.5A \tag{3}$$

$$I_2 = 0.816 I_d = 0.816 \times 82.5 = 67.32A \tag{4}$$

$$I_1 = 29.78A \tag{5}$$

$$S = 3U_2I_2 = 3 \times 97.33 \times 67.32 = 19 \cdot 657KW \tag{6}$$

2.3 Thyristir Selection

The transformer parameters are used as rating parameter constraints to select the thyristor. When selecting the rated parameters of the thyristor (SCR, silicon-controlled rectifier) in the power system, it is necessary to take into account the operating environment and practical application requirements. When considering the rated voltage, the rated voltage of the thyristor must be greater than the maximum reverse voltage that may occur in the circuit, and should be selected with a certain safety margin, usually 1.5 times the rated voltage or higher, in order to cope with voltage shocks and transient over-voltage and other issues [5]. Considering the rated current, the rated current of the thyristor needs to be higher than the actual application of the maximum load current, in some applications (such as start-up or short-term overload conditions), the thyristor may experience a short period of high peak currents, should ensure that the peak current capacity is sufficient, so there should be a certain safety margin when selecting the rated voltage, usually 1.5 times or higher.

The RMS value of the current flowing through the thyristor is

$$I_{VT} = I_d \text{¨}M\sqrt{3} = 82.5\text{¨}M\sqrt{3} = 47.63A \tag{7}$$

The average on-state current is

$$I_{T(AV)} = I_{VT}\text{¨}M1.57 = 30.34A \tag{8}$$

Therefore, when the thyristor rated parameters to take twice the margin

$$I_N \geqslant 2\times I_{T(AV)} = 2\times 30.34 = 60.68A \tag{9}$$

So take the thyristor rated current as 100A

Selection of rated voltage taking into account grid fluctuations

$$U_N \geqslant \sqrt{6}U_2(1+5\%)\times 2 = 500.66V \tag{10}$$

Therefore, the rated voltage can be taken as 600V.

In summary, a thyristor with a rated current of 100A and a rated voltage of 600V should be selected to design the circuit.

2.4 Thyristor protection design

In power electronic circuits, in addition to the proper selection of power electronic device parameters and good design of driving circuits, the use of appropriate overvoltage protection, overcurrent protection, du/dt protection and di/dt protection is also necessary.

2.4.1 Overvoltage protection

The overvoltage that may occur in power electronic devices are classified into exogenous and endogenous overvoltage. Exogenous overvoltage include operational overvoltage and lightning overvoltage, and endogenous overvoltage include phase change overvoltage and shutdown overvoltage. We mainly consider phase change overvoltage suppression. Due to the thyristor or with the full-control device in reverse parallel with the continuous current diode in the end of the phase change cannot be immediately restored to the blocking capacity, and therefore a larger directional current flows through the residual carrier recovery, and when the blocking capacity is restored, the reverse current is reduced, the current will be due to the sudden change of the line inductance in the thyristor cathode and anode, or diode in reverse parallel with the full-control device terminals to produce an over-voltage [6]. In order to protect the thyristor, to take the RC overvoltage suppression circuit is the most common. As shown in Figure 3

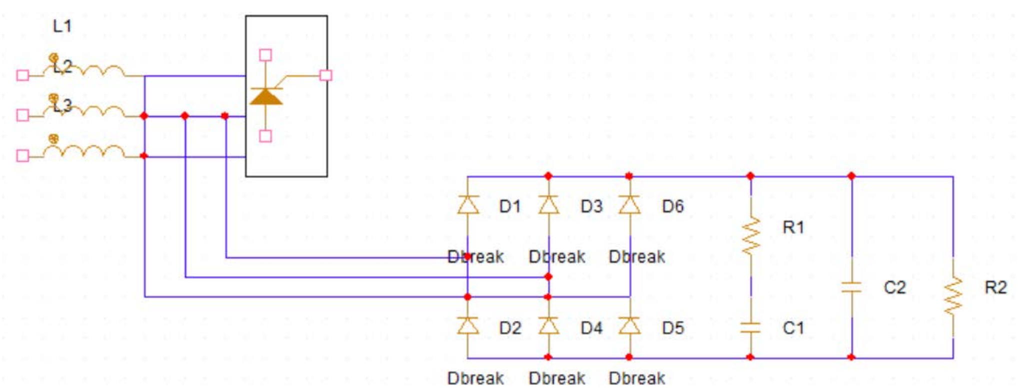

Fig. 3 Schematic diagram of RC overvoltage protection

2.4.2 Overcurrent protection

Overcurrent may occur when power electronic circuits are not operating properly or when faults occur. Overcurrent is classified as either overloads or short circuits. Fast fuses, DC fast circuit breakers and overcurrent relays are more commonly used measures. Fast fuses are widly used, as shown in Figure 4

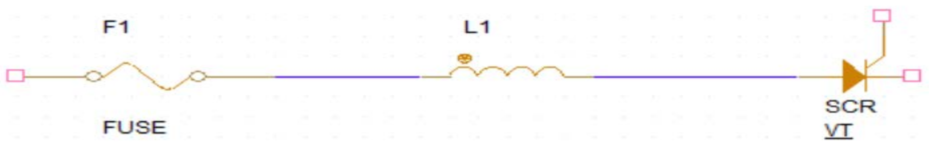

Fig. 4 Fast Acting Fuse Application

2.4.3 Buffer circuitry to suppress du/dt and di/dt

Buffer circuits are also known as absorption circuits. It can suppress the internal cause overvoltage, du/dt or overcurrent and di/dt of power electronics and reduce the switching losses [7]. Turn-off buffer circuits are also known as du/dt suppression circuits and turn-on buffer circuits are also known as di/di suppression circuits.Figure 5 shows a di/dt buffer circuit and Figure 6 shows the du/dt buffer circuit.

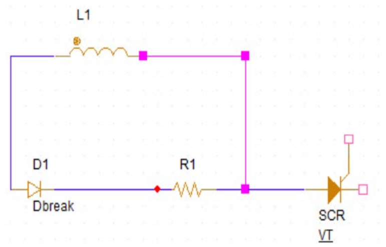

Fig. 5 di/dt buffer circuit

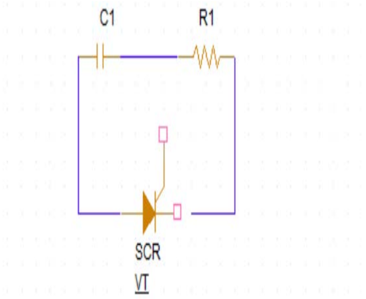

Fig. 6 du/dt buffer circuit

2.5 Thyristor protection design

2.5.1 Synchronous transformer design and phase selection for synchronous voltage

The AC side of the power supply to the thyristor rectifier circuit is usually from the power grid, the frequency of the grid voltage is not fixed, but will have certain fluctuations in the allowable range. Trigger circuit should ensure that the operating frequency and the frequency of the main circuit AC power supply in addition to the same, should also ensure that each thyristor trigger pulse and the AC voltage applied to the thyristor to maintain a fixed and correct phase relationship, which is the trigger circuit phase [8].

The use of a synchronous transformer, the primary side of the grid into the main circuit power supply, the secondary side of the synchronous voltage signal, so that the synchronous voltage determined by the trigger pulse frequency and the main circuit thyristor voltage frequency is always the same [9].

The synchronizing voltage of VT1 should lag ua 180°, and the same correspondence exists for the other five thyristors, i.e. the synchronizing voltage should lag the main circuit voltage by 180°. For the common cathode group of VT4, VT6 and VT2, their cathodes are connected to ua, ub and uc respectively, which can be obtained by simply expressing their main circuit voltages as -ua, -ub and -uc respectively.

According to the main transformer using Y/Y12 connection, the synchronous transformer should be used Yy6y12 connection, the following figure is the synchronous transformer and rectifier transformer connection and vector diagram, the following table is the result of synchronous voltage selection. Figure 7 shows the connection of synchronous transformer and rectifier transformer. As shown in Figure 8 as a vector diagram of the connection

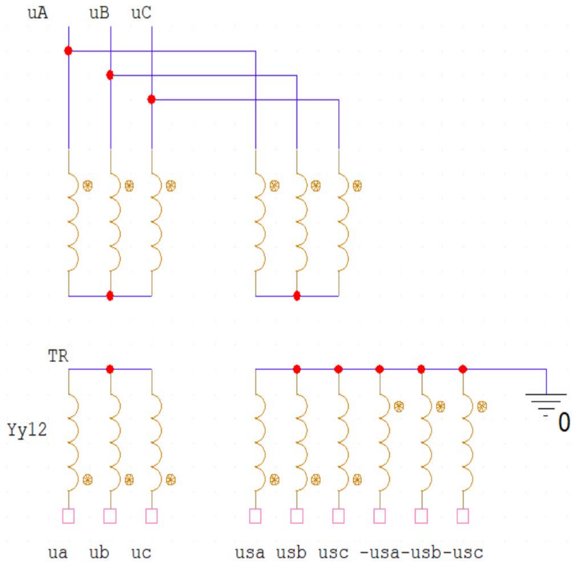

Fig. 7 Synchronous and rectifier transformer connections

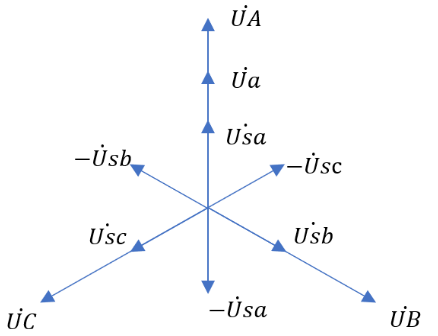

Fig. 8 Vector diagram of the connection

The synchronous voltage of each thyristor of the three-phase fully controlled bridge can be tabulated to obtain Table 1

Table 1. The synchronous voltage of each thyristor

Thyristor	VT1	VT2	VT3	VT4	VT5	VT6
Main circuit voltage	+ua	-uc	+ub	-ua	+uc	-ub
Synchronized voltage	-usa	+usc	-usb	+usa	-usc	+usb

In order to prevent the grid voltage waveform distortion on the trigger circuit interference, the synchronous voltage can be R-C filtering, when the R-C filter hysteresis angle of 60 °, the synchronous voltage selection results shown in Table 2.

Table 2. The synchronous voltage of each thyristor after filtering

Thyristor	VT1	VT2	VT3	VT4	VT5	VT6
Main circuit voltage	+ua	-uc	+ub	-ua	+uc	-ub
Synchronized voltage	-usb	+usa	-usc	+usb	-usa	+usc

2.5.1 KJ004 Thyristor Phase Shift Trigger Circuit

This design uses the KJ004 trigger circuit design. KJ004 Thyristor phase shifting trigger circuit is suitable for single-phase, three-phase fully controlled bridge power supply device, for the Thyristor dual pulse phase shifting trigger. In the phase-shift triggering circuit, the role of KJ004 is crucial, it through the phase-shift control, so that the thyristor in the different phases of the alternating current conduction, to achieve precise control of the load. KJ004 in the thyristor phase-shift triggering circuit in the role of the key and multi-benefits make it become the ideal choice for many industrial and household appliances control system. It not only improves control accuracy and efficiency, but also simplifies circuit design and enhances system reliability and stability.

Three-phase bridge triggering circuit consists of three KJ004 integrated block and a KJ041 integrated block (KJ041 is composed of 12 diodes inside the six or gate) and some of the discrete components, can form a six-way double-pulse, and then six transistors for pulse amplification, respectively, connected to the gate of VT1, VT2, VT3, VT4, VT5, VT6, the internal schematic diagram of the KJ004 and 6-way double-pulse analogue integrated trigger circuit is shown in the figure.

2.6 Trigger circuit power supply design

This article uses a combination of LM7815, LM7915, and a power transformer to design a DC regulated power supply. The circuit principle is shown in Figure 9.

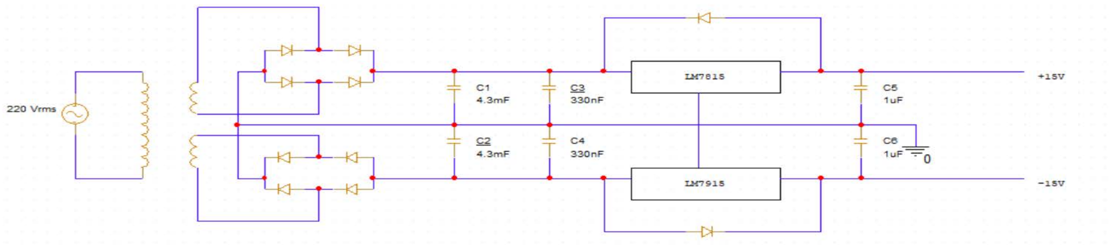

Fig. 9 Trigger Circuit Power Supply Circuit

2.7 General Circuit Diagram

At the end of the design of each module, this paper connects each module to obtain Figure 11

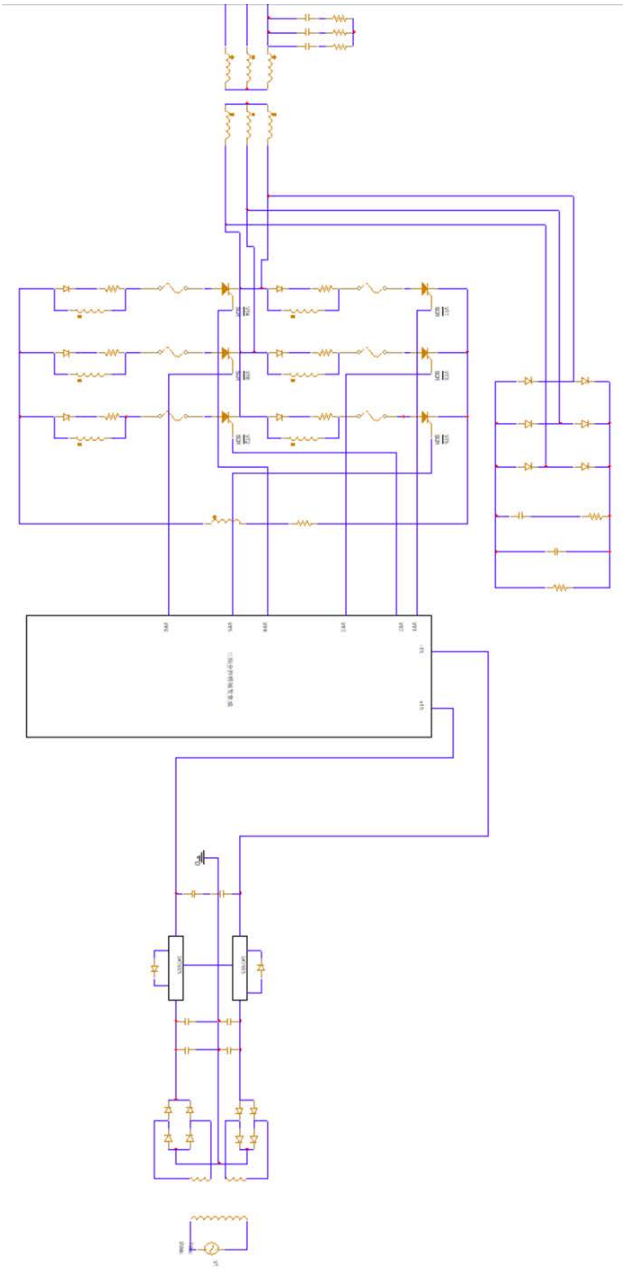

Fig. 10 General Circuit Diagram

3. Matlab simulation analysis

The circuit diagram is simulated using Matlab Simulink tool as shown in Fig. 11.

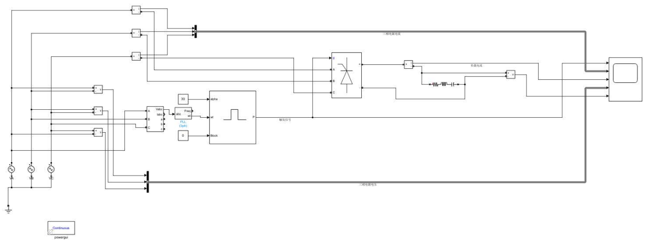

Fig. 11 Circuit Diagram

However, the circuit lines were found to be cumbersome and the output image was messy, and then optimized, as shown in Figure 12.

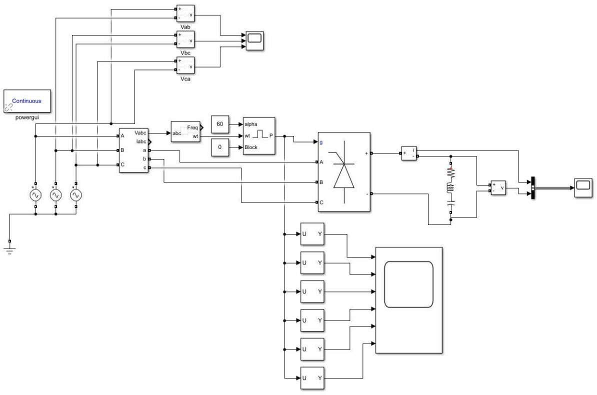

Fig. 12 Optimized Circuit Diagram

The pulse image, the input image and the output image can be obtained as shown in Figure 13, Figure 14 and Figure 15.

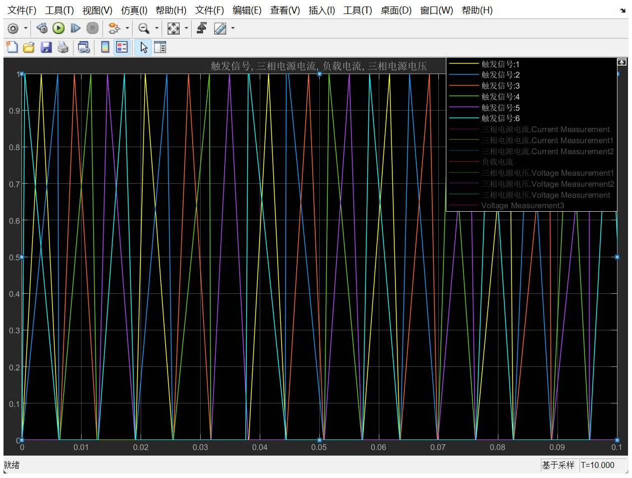

Fig. 13 Pulse image

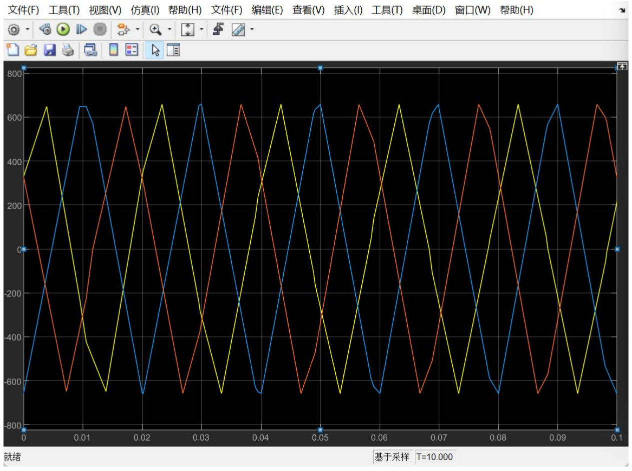

Fig. 14 Input image

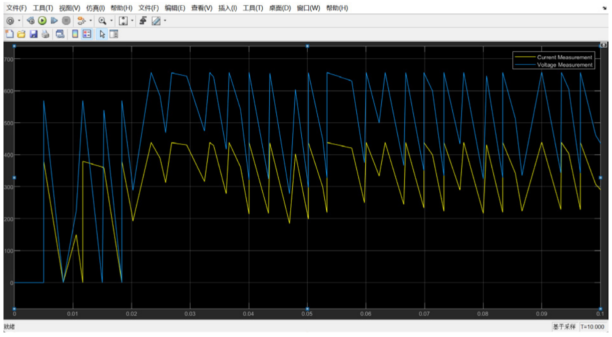

Fig. 15 Output image

It was found that the pulse waveform and output waveform were not satisfactory. Checking the information, it is found that the experiment time is too long which makes the output waveform incomplete and generates distortion, change the experiment time from 10s to 0.1s [10]. get the experimental results(Figure 16 and Figure 17).

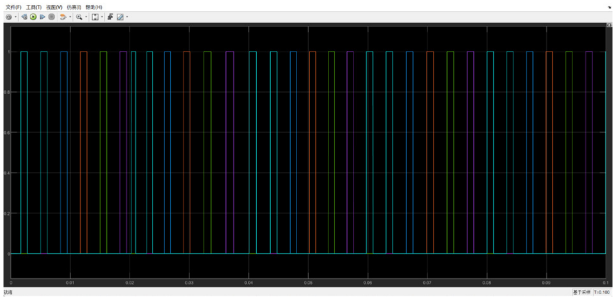

Fig. 16 Pulse image

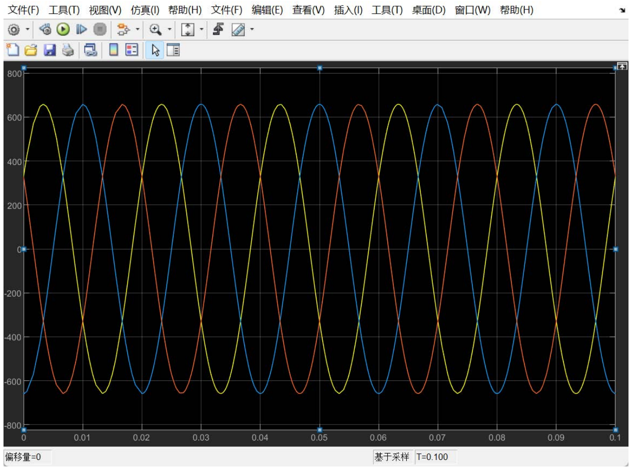

Fig. 17 Input image

The output image is shown Figure 18-21.

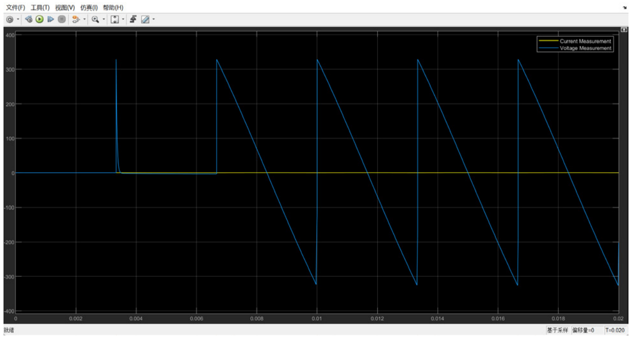

Fig. 18 Output image(α=90°)

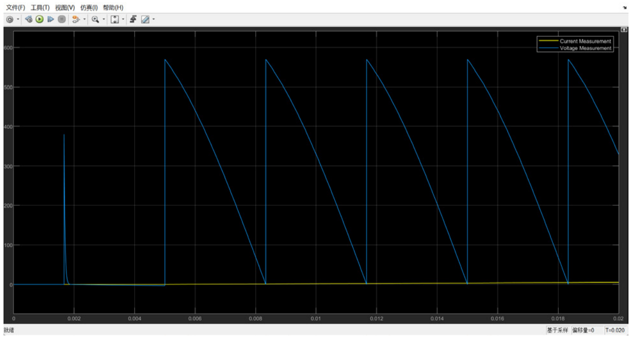

Fig. 19 Output image(α=60°)

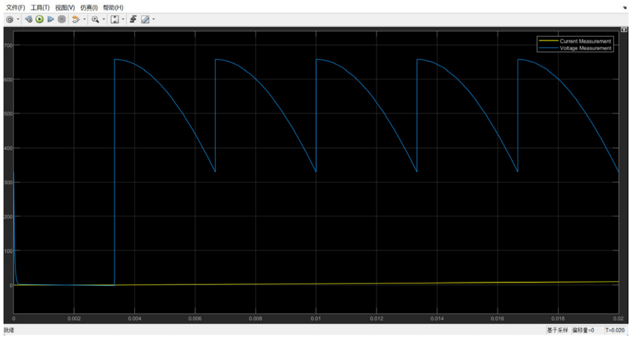

Fig. 20 Output image(α=30°)

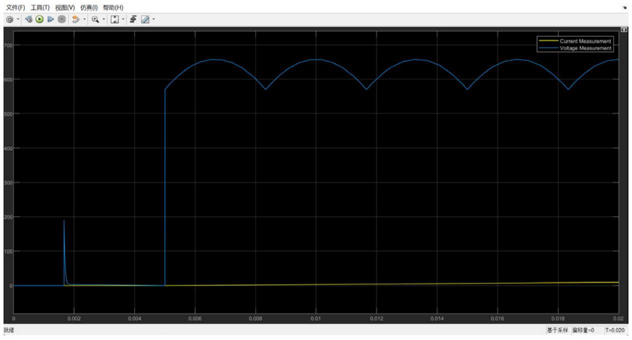

Fig. 21 Output image(α=0)

4. Conclusion

The paper presents a comprehensive design and analysis of a three-phase fully controlled bridge rectifier circuit, a critical component in various industrial and power applications. The transformer design was calculated to meet the specified load requirements, ensuring that the secondary phase voltage and currents are appropriately matched to the DC motor's needs. Thyristor selection was guided by stringent criteria to withstand the maximum reverse voltage and handle peak currents that may arise during operation. Protection mechanisms, including overvoltage and overcurrent protections, were integrated to safeguard the circuit from potential faults and operational anomalies.The trigger circuit, a vital component for precise control of the thyristors, was carefully designed using the KJ004 phase shift trigger circuit. This design not only ensures accurate load control but also contributes to the simplification of the overall circuitry, enhancing system reliability and stability.A regulated DC power supply, combining LM7815, LM7915, and a power transformer, was developed to provide a stable power source for the trigger circuit. The general circuit diagram, resulting from the integration of all modules, was simulated using Matlab. Initial simulation results indicated the need for optimization to address issues related to waveform distortion and incomplete output due to prolonged experiment time. Adjustments led to improved pulse, input, and output waveforms, demonstrating the effectiveness of the design under different triggering angles.

In summary, this paper has successfully demonstrated an optimal design approach for a three-phase fully controlled bridge rectifier circuit. The findings underscore the importance of a balanced consideration between circuit performance and power consumption, leading to a robust and efficient solution suitable for high-power applications. The design and simulation analysis presented herein provide a solid foundation for further research and practical implementation in the field of power electronics.

However, we still have a long way to go. In the face of the rapid development of power electronics technology, the future development of the three-phase fully controlled bridge rectifier circuit will focus on achieving higher energy efficiency and intelligent control. With the emergence of new semiconductor materials such as Silicon Carbide (SiC) and Gallium Nitride (GaN), it is expected that the application of these materials will significantly enhance the efficiency and power density of the circuit. At the same time, the integration of deep learning algorithms and artificial intelligence technology will enable the rectifier circuit to adapt more intelligently to the dynamically changing working environment, achieving adaptive optimization control.

References

[1] Li, Shue, and Feng Lv. "MATLAB-based Three-Phase Full-Controlled Bridge Rectifier Circuit Simulation." Proceedings of the 2012 Second International Conference on Intelligent System Design and Engineering Application, 2012, pp. 345-347. IEEE, 2012. https://doi.org/10.1109/ISdea.2012.700

[2] B. Ilango, R. Krishnan, R. Subramanian, and S. Sadasivam "Firing Circuit for Three-Phase Thyristor-Bridge Rectifier", IEEE, Transactions on Industrial Electronics and Control Instrumentation, Vol. IECI-25, No. 1, FEB. 1978.

[3] Singh, Arvind R., et al. "A high-efficiency poly-input boost DC–DC converter for energy storage and electric vehicle applications." Nature, 6 Aug. 2024, www.nature.com/articles/s41598-024-69254-1.

[4] Alcaide, Abraham Marquez, et al. "Design and Control for High-Reliability Power Electronics: State-of-the-Art and Future Trends." IEEE Journal of Emerging and Selected Topics in Industrial Electronics, vol. 5, 2024, pp. 50-61. https://doi.org/10.1109/JESTIE.2024.0000000.

[5] R. F. Dyer, "The rating and application of SCR's designed for power switching at high frequencies", IEEE Trans. Industry and General Applications, vol. IGA-2, pp. 5-15, January-February 1966.

[6] Wang, Zhaoan, and Jinjun Liu. *Power Electronics Technology*. 5th ed., China Machine Press, 2009.

[7] He, Yikang, and Zaiping Pan. *Fundamentals of Power Electronics Technology*. China Machine Press, 1995.

[8] Alves, E., Bergna-Diaz, G., Brandao, D., and Tedeschi, E. "Sufficient Conditions for Robust Frequency Stability of AC Power Systems." IEEE Conference Publication, IEEE Xplore, 21 July 2022.

[9] Li, Xubao. *Power Electronic Devices and Their Applications*. China Machine Press, 1996.

[10] Zhang, Sen, and Zhengliang Zhang. *MATLAB Simulation Technology and Application Examples Tutorial*. China Machine Press, 2004.