Analysis of Control Strategy of Three-phase Bridge Fully Controlled Rectifier Circuit Based on PID Control

Zhao Yao *

College of Physics and Electronic Engineering, Northwest Normal University， Lanzhou, Gansu Province, 730000, China

* Corresponding Author Email: 358372934@qq.com

Abstract. At the present stage of industrial production in China, rectifier circuits still have an important position, and their safe, reliable, and efficient operation is still a necessary issue to be explored in the development of power electronics technology. Therefore, this paper will build an improved three-phase bridge rectifier circuit based on the traditional three-phase bridge fully controlled rectifier circuit, replacing the thyristor with an insulated gate bipolar transistor (IGBT) under the same basic principle, so that it can be more easily controlled by industrial intelligence. The PID controller is introduced to make the output voltage of the rectifier circuit gradually converge to a certain value by continuously correcting the calculation of the trigger angle α and the calculation of the voltage and current values. The simulation results show that the PI-controlled three-phase bridge fully controlled rectifier circuit model established in the paper makes the output of the circuit eventually stabilize under the influence of the closed-loop control, and the simulation results reach the expected value and show strong robust stability. For industrial applications, improving the safety, reliability, efficiency, and flexibility of bridge rectifier circuits is of good reference in practical engineering applications.

Keywords: Three-phase bridge fully controlled rectifier circuit; PID controller; IGBT; Trigger angle; Closed-loop control

1. Introduction

China's power system is mainly based on AC distribution, many cases will need to transform the load side of the AC power, and generally need to go through the AC to DC rectification process. And with the vigorous development of China's ultra-high voltage AC transmission technology and the extensive access to a high proportion of new energy, large-scale power electronic equipment access to the power grid, the current application of rectifier circuit in engineering, three-phase bridge fully controlled rectifier circuit is extremely widely used, so the reliable operation of the rectifier bridge circuit is particularly important, the study of its control strategy can effectively improve the efficiency and safe and reliable operation of the power grid.

In modern industrial process control, PID control is widely used because of its simple structure and good adaptability, and many advanced controls use PID control as a basis. The paper[1] investigates the use of time-optimal control (also known as Bang-Bang control) in the computer monitoring system of hydroelectric power plants to give a segmentation control algorithm combined with Deadband digital PID control; the students from South China Normal University propose the application of motor PID closed-loop system on the intelligent trolley for the accurate control of the speed of the trolley, which can better control the speed of the trolley accurately[2]; the paper[3] mainly The paper[4] proposes to apply PI-PD control method to the control of hydropower units in the microgrid, analyzes the control effect of conventional PID control and PI-PD control on hydropower units by using frequency domain analysis, and proposes the parameter adjustment method to improve the dynamic response process of hydropower units. Dr. Jiarui Cui from the School of Automation addresses the traditional control method of permanent magnet synchronous motor, which is easily affected by uncertainties such as motor parameter changes and load disturbances. A variable-domain adaptive fuzzy PID composite control strategy is proposed to achieve self-tuning of control parameters and self-adjustment of control rules using variable-domain fuzzy control.[5] As one of the most widely used rectifier circuits in industry, the three-phase bridge fully controlled

rectifier circuit has been developed in a mature technology.[7]The paper[6] compares the current application of multi-physics field modeling technology and multi-physics field analysis in IGBT summarizes the problems and difficulties and analyzes the future trend of this technology in IGBT. The paper[8] designs a radial basis function RBF network with no local minima problem and good classification characteristics to identify the faults of different thyristors; the paper[9] completes the simulation study of single-phase/three-phase single-switch Buck-type PFC based on PI control in SIMULINK module and analyzes and demonstrates the performance indexes of the system based on PI control; the paper The literature[10] analyzes the transmission principle of AC induction power transfer system, several models of loosely coupled transformers, and establishes a compensated AC induction power transfer model. In summary, the literature is relatively vacant for the study of the control of the trigger angle of a three-phase bridge full-bridge rectifier circuit combined with modern industrial intelligent control.

In this paper, we will combine the basic knowledge of power electronics, power systems, circuits, automatic control principles, and other related majors, and use the MATLAB visual simulation tool Simulink to establish the simulation model of a three-phase bridge fully controlled rectifier circuit based on PID closed-loop control, analyze the control strategy of rectifier waveform to solve the working principle of the existing three-phase bridge fully controlled rectifier circuit built based on IGBT The problem of the effect of different pulse triggering angle α and commutation overlap angle γ on the rectifier waveform is analyzed by constructing a 6-pulse bridge circuit of the EHV DC transmission commutator in Simulink. Based on the simulation model of the three-phase bridge fully controlled rectifier circuit constructed based on IGBT, the PID control system is added for control strategy analysis.

2. Principle content

2.1. Operating principle of three-phase bridge fully controlled rectifier circuit

2.1.1 Operating Principle of the Fully Controlled Device IGBT

Insulated gate bipolar transistors (IGBT) are also three-terminal devices with gate G, collector C, and emitter E. High input impedance, fast switching speed, good thermal stability, reduced saturation voltage, low driving power, a simple driving circuit, high withstand voltage, and high capacity, combining the advantages of MOSFETs and GTRs, are widely used in electronic equipment and agricultural machinery. The working principle and characteristics of IGBT modules and related considerations are studied to deepen the understanding of IGBT modules and promote their use in practice. [11]

The IGBT module has a MOSFET input and a PNP transistor output. The principle of the IGBT module is shown in Figure 1, and the equivalent circuit diagram and symbols are shown in Figure 2.

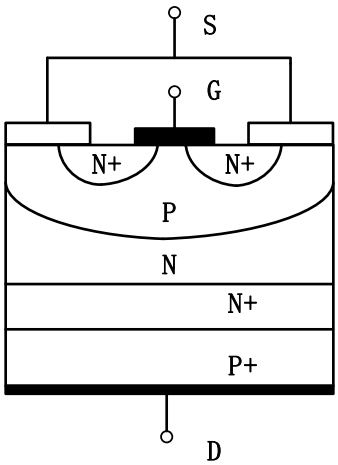


Figure 1 Schematic diagram

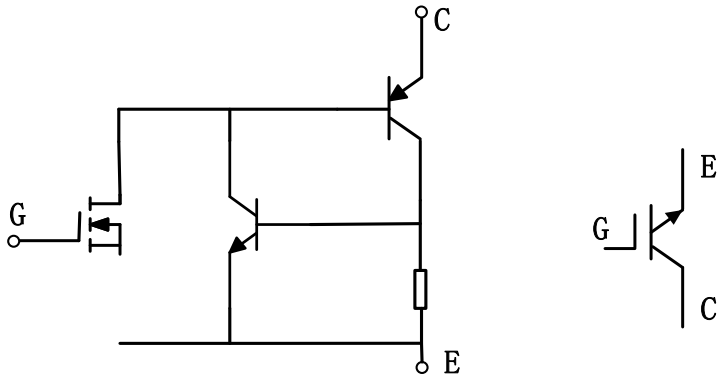


Figure 2 Equivalent circuit and symbol of IGBT

The turn-on and turn-off of the IGBT module are controlled by the gate voltage. Under the gate forward voltage, the MOSFET channel appears and provides the base current to GTR, turning the IGBT on; under the gate reverse voltage, the MOSFET channel disappears, turning the IGBT off.

2.1.2 Three-phase bridge fully controlled rectifier circuit principle

The rectifier circuit is used to convert AC power into DC power and supply DC power equipment, the principle of which is shown in Figure 3, where the three thyristors VT_1, VT_3, and VT_5 connected together at the cathode are called the common cathode group; the three thyristors VT_4, VT_6, and VT_2 connected together at the anode is called the common anode group. The circuit in the operating state of the common cathode group and common anode group each has a thyristor in the conduction state, thyristor pulse according to VT_1-VT_2-VT_3-VT_4-VT_5-VT_6 in the order of conduction, phase difference of 60 °. The pulses of VT_1, VT_3, and VT_5 for the common cathode group and VT_2, VT_4, and VT_6 for the common anode group are 120° apart. The pulses of the upper and lower bridge arms of the same phase, i.e., VT_1 and VT_4, VT_2 and VT_5, VT_3 and VT_6, differ by 180°.

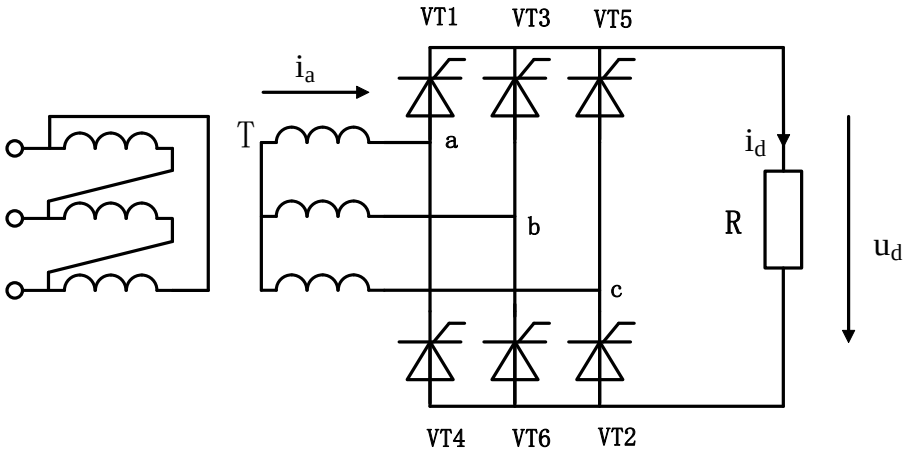


Figure 3 Principle of three-phase bridge fully controlled rectifier circuit

When α=0°, the thyristors are in a natural phase change point at the phase change. At this time, for the three thyristors in the common cathode group, the one with the largest AC voltage value connected to the anode is on. For the three thyristors in the common anode group, the one with the smallest AC voltage connected to the cathode is on. Therefore, at any moment, the common cathode group and the common anode group have a thyristor in the conduction state, and the voltage applied to the load is a certain line voltage. The operating waveform of the circuit is shown in Figure 4.

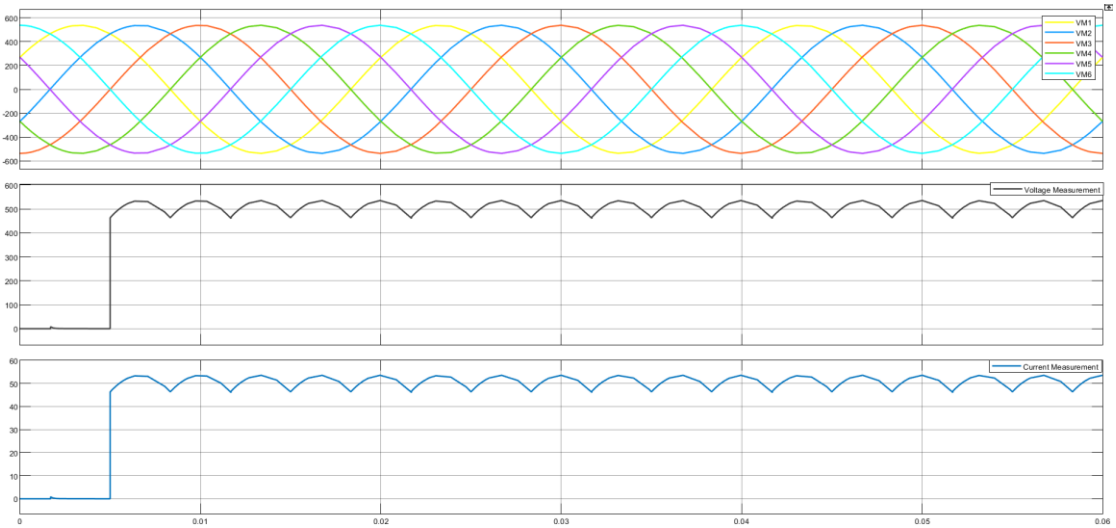


Figure 4 Waveform of three-phase bridge fully controlled rectifier circuit with resistive load α=0°

Table 1 Three-phase bridge fully controlled rectifier circuit resistive load α = 0 ° when the thyristor work[12]

Time Period	I	II	III	IV	V	VI
Thyristor conducting in the common cathode group	VT_1	VT_1	VT_3	VT_3	VT_5	VT_5
Thyristor conducting in the common anode group	VT_6	VT_2	VT_2	VT_4	VT_4	VT_6
Rectified output voltage u_d	u_{ab}	u_{ac}	u_{bc}	u_{ba}	u_{ca}	u_{cb}

When the trigger angle α is changed, the operation of the circuit will change.

The waveform of rectified output voltage ud pulsates six times in one cycle and the waveform of each pulsation is the same, so when calculating its average value, only one pulsation waveform is needed. When the rectifier output voltage is continuous (with resistive load, or with resistive load α≤60°) the average value is

$$U_d = \frac{1}{\frac{\pi}{3}} \int_{\frac{\pi}{3}+\alpha}^{\frac{2\pi}{3}+\alpha} \sqrt{6} U_2 \sin \omega t d(\omega t) = 2.34 U_2 \cos \alpha \tag{1}$$

With resistive load $\alpha > 60°$, the average value of rectifier voltage is

$$U_d = \frac{3}{\pi} \int_{\frac{\pi}{3}+\alpha}^{\pi} \sqrt{6} U_2 \sin \omega t d(\omega t) = 2.34 U_2 [1 + \cos(\frac{\pi}{3} + \alpha)] \tag{2}$$

The average value of rectification output current is

$$I_d = \frac{U_d}{R} \tag{3}$$

2.2. PID control strategy analysis

PID control is a closed-loop control (feedback control), P: proportional, I: integral, D: differential. PID control includes PI control and PD control, PID controller is mainly in accordance with the system error, with the help of differential, integral and proportional calculation of the control amount to implement control, to ensure that the automatic control system in the case of interference can also be a smooth operation. The closed-loop control process is shown in Figure 5.

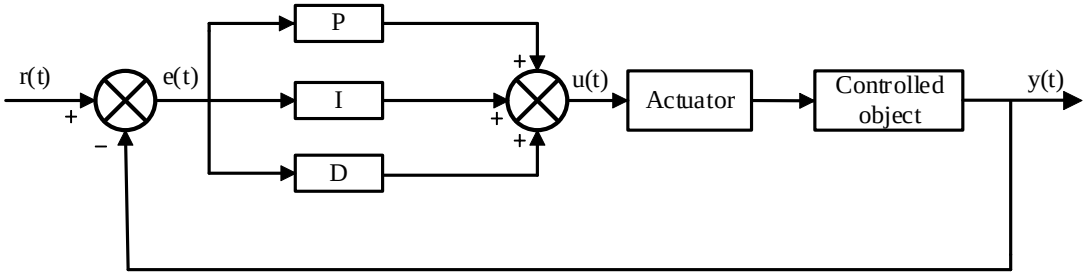


Figure 5 PID closed-loop control flow chart

A PID controller is also known as a proportional + integral + differential controller. the time domain expression for a PID controller is.

$$u(t) = K_P(e(t) + \frac{1}{T_i}\int_0^t e(t)dt + T_d\frac{de(t)}{dt}) = K_P e(t) + K_i\int_0^t e(t)dt + K_d\frac{de(t)}{dt} \tag{4}$$

Where u(t) is the output signal of the PID controller and e(t) is the input signal of the PID controller, which is the error signal of the system. Kp is called the proportional coefficient, Ki is the integral coefficient, Kd is the differential coefficient, and Ti,Td are called the integral and differential time constants, respectively.

The transfer function is.

$$G(s) = \frac{U(s)}{E(s)} = K_P(1 + \frac{1}{T_i s}T_d s) = K_P + K_i\frac{1}{s} + K_d \tag{5}$$

3. Simulation analysis of three-phase bridge fully controlled rectifier circuit based on PID control

3.1. Model Construction

3.1.1 Circuit structure diagram and simulation model

In the MATLAB environment, I modeled the three-phase bridge fully controlled rectifier circuit using Simulink's various components according to Figure 6 (replacing the thyristor in the traditional three-phase bridge rectifier circuit with an IGBT and connecting a diode at each IGBT end for current continuation) and adding a control link (PI control) (Figure 7).

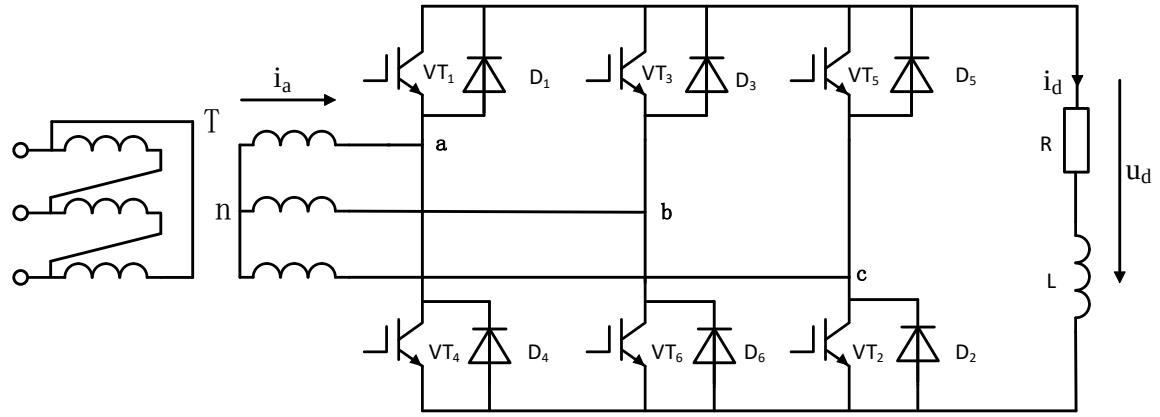


Figure 6 IGBT three-phase bridge fully controlled rectifier circuit structure diagram

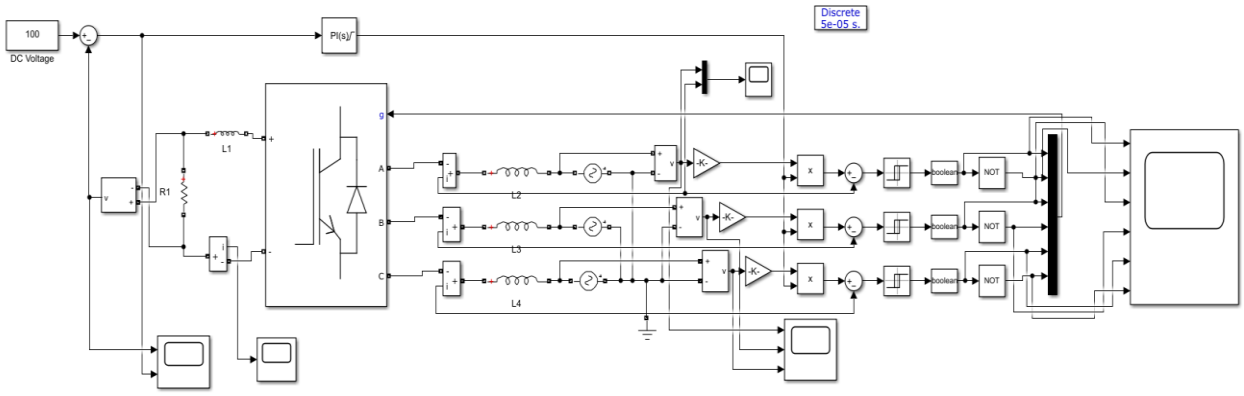


Figure 7 Simulation model of three-phase fully controlled rectifier circuit

3.1.2 Model parameter setting

1) AC voltage source parameter setting: set the AC peak phase voltage to 100V, frequency to 25Hz, and phase difference 120°, to improve the control effect, after the three-phase power supply series into an 8mH filter inductor.

2) Parameter setting of the load: select R=8Ω, L=1H.

3) Module parameters of the full-bridge circuit: buffer resistor Rs size is 100kΩ, buffer capacitor is inf, forward voltage is [0,0].

4) The Gain module value is set to 1000.

5) The proportional (P) of the PI control module is set to 9.06 and the integral (I) is set to 98.09; the limit of phase angle is set to [0,90].

3.2. Simulation results and analysis

The PI control module is added to the simulation to form a closed-loop control, which makes the output voltage of the rectifier circuit gradually converge to a constant value and the error gradually converges to 0 by continuously correcting the calculation of the trigger angle and the voltage and current values. The output voltage of the three-phase AC circuit is maintained at 100V with an error value of 0.

Figure 8 shows the trigger waveforms corresponding to the six IGBTs, from the first natural phase change point of the positive half cycle at 30° from the x-axis. When α=0°, the delay time of the first IGBT is 0.0033s. The trigger phases of VT1, VT2, VT3, VT4, VT5, and VT6 are in turn different by 60°, and the phase of each IGBT is delayed by 0.0066s. At α=30°, the trigger phase of each thyristor is further delayed by 0.0033s in turn.

Figure 9 shows the waveform of output voltage and error. As shown in the figure below, the voltage across the resistor of the output circuit increases from zero moments to 100 and then stabilizes, while the error value gradually approaches 0. This is due to the control effect of PI on the circuit, which makes the output of the circuit eventually stabilize under the influence of closed-loop control. The simulation results achieve the expected value.

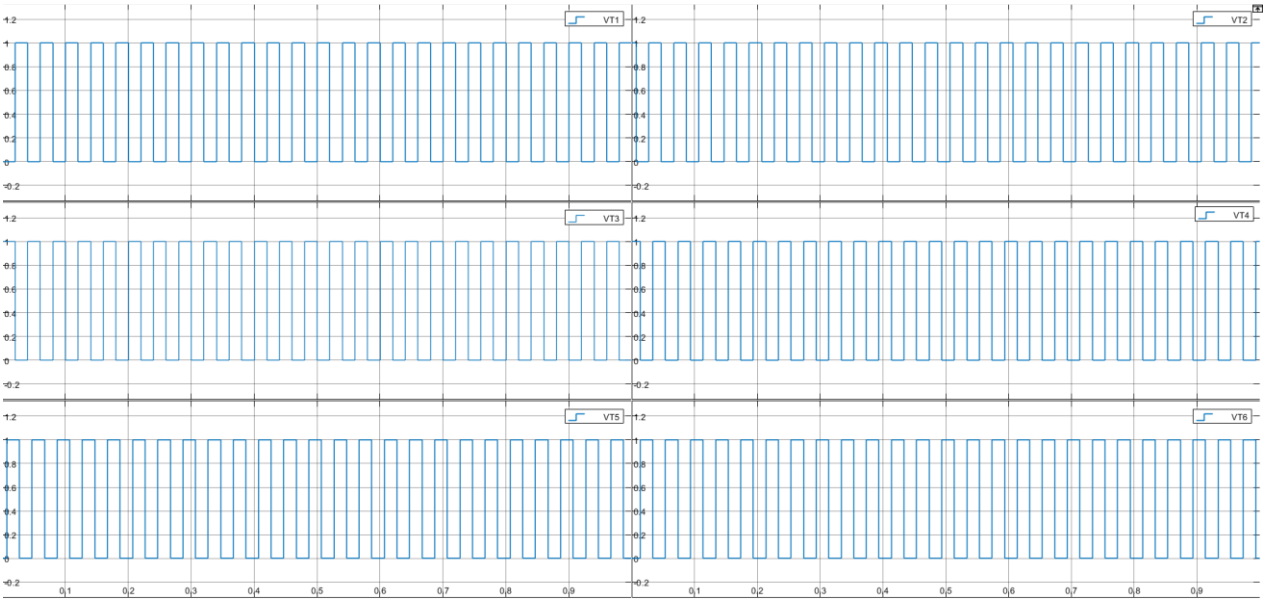


Figure 8 IGBT trigger pulse diagram

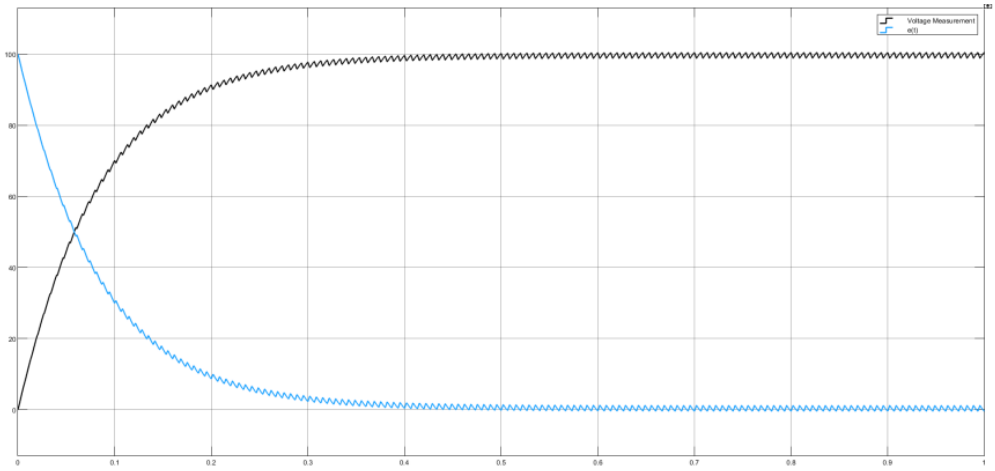


Figure 9 Output voltage and error waveform

Figure 10 shows the waveform of the output current. From the quantitative analysis, the relationship between the output current and output voltage is I=U/R, so the current waveform shows the same trend as the voltage waveform.

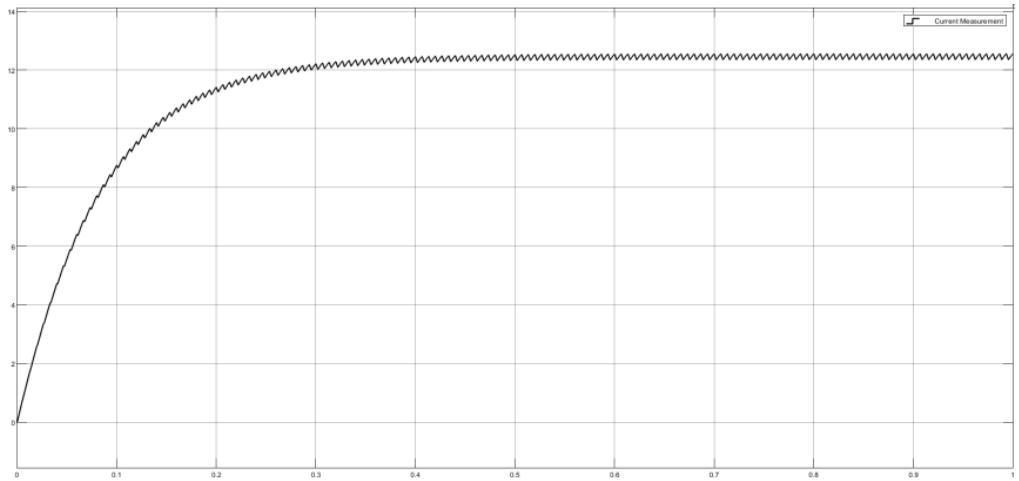


Figure 10 Output current waveform

4. Conclusion

In this paper, the traditional three-phase fully-controlled rectifier circuit is reasonably improved while keeping its basic principle unchanged, and a simulation model is established to make it easier for industrial intelligent control. The PI closed-loop control is also combined with the three-phase bridge fully controlled rectifier circuit. The correctness of the established model is verified by simulation analysis. By using MATLAB simulation, the effect of different parameters on the rectifier circuit can be observed visually without complicated operation experiments, i.e., good simulation waveforms are obtained and effective control of the output value is achieved. That is, it reflects the flexibility of power electronics technology, which can use a variety of power electronic devices to complete the power conversion under the same basic principle, and through the combination with PI control, it also makes the three-phase fully controlled rectifier output voltage accuracy significantly improved. In industrial applications, DC power equipment will not be damaged due to rectification failure, which improves the safety and reliability of industrial production. The rectification control circuit studied in this paper can achieve the expected goal through simulation, which is of good reference in practical engineering applications.

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