Research on Harmonic Suppression of High Temperature Boiler Based on Three-phase PWM Rectifier

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Abstract. Traditional boiler temperature control is based on thyristor voltage regulation, and the output AC voltage is controlled by controlling the trigger angle \( \alpha \) of thyristor, so that the boiler temperature can be controlled in the pre-set range. However, this way of voltage regulation and temperature control will cause serious harmonic pollution to the power grid, and the output current has high harmonic content and low power factor. At the same time, the traditional three-phase load connection mode generally adopts star connection, and the load is pure resistive silicon carbide. Because of long-term use, the aging of silicon carbide heating rod is different, in fact, it is asymmetric load, three-phase load. The unbalance will cause three-phase unbalance, which will make the voltage of a certain phase exceed the rated working voltage of the heating rod, and greatly reduce the service life of the heating rod. Therefore, in order to improve the efficiency of power supply, reduce harmonic pollution and solve the problem of three-phase unbalance, this paper proposes a three-phase PWM rectifier circuit, which converts AC to DC, and realizes DC voltage regulation and temperature control through PI regulator. In this paper, the feasibility of the scheme is verified by simulation and comparative analysis.

1. Introduction

At present, most of the domestic boilers are mainly fuel oil or coal, and a large amount of residue and waste gas will be generated during the combustion process, which not only has adverse effects on human life, but also causes great pollution to the environment. With the continuous advancement of modern society, electric energy is gradually replacing fuel energy. The electric boiler can directly convert electric energy into heat energy. It is a high-tech mechatronics product; small size, high efficiency, low noise and no pollution are several characteristics of electric boilers. In addition, electric boilers have heat supply stability. The operation is safe and reliable, and the degree of automation is high. It is an ideal energy-saving and environment-friendly heating equipment [1-3]. However, the traditional temperature-controlled power supply mode works in the low frequency band, and the efficiency is low; and the power supply mode is likely to cause serious harmonics on the grid side and the load, causing waveform distortion of the power grid, thereby forming a grid pollution [4-6].

With the rapid development of power semiconductor switching device technology, high-frequency, high-voltage and high-current power semiconductor composite devices represented by power switching transistor MOSFETs (Power Field Effect Transistors) and IGBTs (Insulated Gate Bipolar Transistors) The emergence of PWM control technology and the development of power electronic converter technology, the emergence of various types of converter based on pulse width modulation (PWM) control, and these converters have been in some areas The application has achieved good
results [7]; the power switching devices used in current PWM rectifiers are mostly IGBTs, the switching device frequency can be up to K level, and the switching frequency is generally 2-15 kHz. The three-phase voltage type PWM rectifier has the advantages of fast dynamic control response, small current distortion on the grid side, and high power factor [8-10]. Based on the defects of traditional boiler power supply mode and the advantages of PWM rectifier, this paper improves the traditional boiler temperature control power supply mode, and proposes a three-phase PWM rectifier circuit based power supply mode. This power supply method first solves the three-phase unbalance and center point. The offset problem, secondly, this power supply method first converts the alternating current into direct current, and then adjusts the direct current output voltage through the PI regulator to control the boiler temperature; the simulation results show that the power supply mode has a fast dynamic response and the power grid harmonic distortion is small. The power factor is high.

2. Harmonic Analysis of Traditional Boiler Temperature-controlled Power Supply

At present, thyristor regulator is generally used in heating power adjustment of high-temperature boilers in most factories. Thyristor regulator is a high-power device controlled by small current and small power in current industry. Thyristor regulator is a mature and widely used technology for temperature control of boilers. The process of temperature control is actually controlled by controlling trigger angle $\alpha$. The single-phase main circuit is composed of two anti-parallel thyristors and load series connection, as shown in figure 1.

2.1 Analysis of the Traditional Boiler Temperature-controlled Power Supply Circuit

At present, the early AC voltage regulating circuit is still used in the temperature control of high temperature boiler heating system in the market. The topological structure of this circuit is shown in figure 2.

The circuit connects three groups of reverse parallel thyristors in series with the star connected load respectively. Because of the open middle line, if there is a current on the load, at least two phase loads must be required to form a path. To this end, the following requirements are met:
1. The pulse signal emitted by the trigger circuit must be greater than 60°, so that a forward and reverse thyristor can work reliably.

2. The output three-phase AC voltage is adjustable and symmetrical, which requires that the six thyristor trigger signals have phase requirements.

In the circuit of AC voltage regulation and temperature control, the trigger signal of thyristor is symmetrical in positive and negative half-wave. The effective value of output voltage of each phase of thyristor voltage regulation is determined by AC factor angle \( \varphi \) and thyristor control angle \( \alpha \). The effective value of output voltage is shown in expression (1).

\[
U_e = \sqrt{\frac{1}{\pi} \left[ \int_0^\infty (\sqrt{2}U \sin \omega t)^2 \, dt + \int_0^\infty (\sqrt{2}U \sin \omega t)^2 \, d(\omega t) \right]}
\]

\[
= U_e \sqrt{\frac{1}{\pi} \left[ (\pi + \varphi - \alpha) + \frac{1}{2} (\sin 2\alpha - \sin 2\varphi) \right] = f(U, \alpha, \varphi)}
\]

The output voltage \( U_e \) is only related to the input voltage \( U \), the AC factor angle \( \varphi \) and the thyristor control angle \( \alpha \). Without changing the external factors \( (U, \varphi) \), only the thyristor control angle \( \alpha \) can be changed.

1. At \( 0^\circ < \alpha < 60^\circ \), the circuit is in alternating working state, with one thyristor working in each phase and one thyristor working in two phases and the other not working in two phases; at this time, the conduction angle of the thyristor is \( 180^\circ - \alpha \), and at \( \alpha = 30^\circ \), the circuit is in alternating working state at every \( 30^\circ \). As shown in figure 3.

![Figure 3. \( \alpha = 30^\circ \) output waveform](image)

2. At \( 60^\circ < \alpha < 90^\circ \), only two-phase thyristors work in the circuit, while the other phase does not work; the thyristor conduction angle is \( 120^\circ \).

3. At \( 90^\circ < \alpha < 150^\circ \), the circuit is in alternating working state. There are two phases in the three-phase circuit, one thyristor in each phase and two states in which the three-phase thyristor does not work. The conduction angle of thyristor is \( 150^\circ - \alpha \), when \( \alpha = 90^\circ \), the current is in the critical intermittent state; when \( \alpha = 150^\circ \), the thyristor is in the non-working state, and the output voltage is 0.

2.2 Harmonic Analysis of Power Supply Circuit

When thyristor is used as AC voltage regulator, the current and voltage waveforms are short of phase by controlling the voltage of \( \alpha \), and the waveforms are non-sinusoidal, so there are many harmonic components in the output current. The load of the boiler is silicon carbide, which is pure resistance. Although the current output waveforms and effective values are different at different control angles \( \alpha \), they are all positive and negative half-cycle symmetrical, satisfying the Fourier series expansion conditions, thus satisfying expression 2:

\[
f(\alpha) = \begin{cases} 
-g(\alpha + \pi) & -\pi \leq x < 0 \\
g(x) & 0 \leq x < \pi 
\end{cases}
\]
Expansion into Fourier series is an expression (3):

$$f(x) = \frac{a_0}{2} + \sum_{k=1}^{\infty} (a_k \cos kx + b_k \sin kx)$$  \hspace{1cm} (3)$$

Its general term expression (4) is:

$$a_n = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x) \cos nx \, dx \text{ for } n = 0, 1, 2, 3 \ldots$$

$$b_n = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x) \sin nx \, dx \text{ for } n = 0, 1, 2, 3 \ldots$$  \hspace{1cm} (4)$$

By substituting expression (2), expression (5) can be obtained:

$$a_n = \frac{1}{\pi} \int_{-\pi}^{\pi} g(x) \cos nx \, dx \text{ for } n = 0, 1, 2, 3 \ldots$$

$$b_n = \frac{1}{\pi} \int_{-\pi}^{\pi} g(x) \sin nx \, dx \text{ for } n = 0, 1, 2, 3 \ldots$$  \hspace{1cm} (5)$$

When n is an odd number, expression (6) can be obtained:

$$a_n = 2 \int_{0}^{\pi} g(x) \cos nx \, dx \text{ for } n = 1, 3, 5 \ldots$$

$$b_n = \frac{2}{\pi} \int_{0}^{\pi} g(x) \sin nx \, dx \text{ for } n = 1, 3, 5 \ldots$$  \hspace{1cm} (6)$$

2.3 Harmonic calculation of power supply circuit

The effective value of the second harmonic of the voltage $U_n$ at both ends of the boiler load is expressed as (7):

$$U_n = \frac{1}{\sqrt{2}} (a_2^2 + b_2^2)^{\frac{1}{2}}$$  \hspace{1cm} (7)$$

Because the silicon carbide loaded on the boiler is a resistive load, there is a R-fold proportional relationship between harmonic voltage and harmonic current, that is, the expression (8) of harmonic current is as follows:

$$I_n = \frac{1}{\sqrt{2R}} (a_n^2 + b_n^2)^{\frac{1}{2}}$$  \hspace{1cm} (8)$$

The RMS of each harmonic current is expressed by the standard unitary value $I'_n$, and its expression is (9):

$$I'_n = \frac{\text{Effective Value of the } n\text{th Harmonic Wave at } \alpha \text{ Angle}}{\text{Current RMS at } \alpha = 0} = \frac{I_n}{I}$$  \hspace{1cm} (9)$$

When $\alpha = 0$, each phase in the three-phase circuit has a thyristor working. At this time, the voltage on the load is the voltage of each phase. Therefore, the effective value of each load current $I = \frac{U}{R}$ and $U = \frac{U_m}{\sqrt{2}}$ where $U_m$ is the maximum value of single-phase voltage, are substituted for (9) formula to obtain the expression (10):

$$I'_n = \frac{(a_n^2 + b_n^2)^{\frac{1}{2}}}{U_m}$$  \hspace{1cm} (10)$$

It can be seen that the standard unitary value $I'_n$ of the effective value of the harmonic current is related to the control angle $\alpha$. Table 1 shows the basic wave and the harmonic current content at different special control angles.
Table 1 Relationship between harmonic current and trigger angle

| Angle (°) | $I'_1$ | $I'_2$ | $I'_3$ |
|----------|--------|--------|--------|
| 0        | 1      | 0      | 0      |
| 15       | 0.995  | 0.031  | 0.029  |
| 30       | 0.964  | 0.105  | 0.086  |
| 45       | 0.869  | 0.178  | 0.113  |
| 60       | 0.792  | 0.207  | 0.103  |
| 75       | 0.649  | 0.207  | 0.103  |
| 90       | 0.463  | 0.207  | 0.103  |
| 105      | 0.275  | 0.178  | 0.113  |
| 120      | 0.127  | 0.105  | 0.086  |
| 135      | 0.032  | 0.034  | 0.026  |
| 150      | 0      |        |        |

Table 1 shows that:

1. In the boiler temperature control circuit, the harmonic current only contains $n = 6k \pm 1$ sub-harmonic component, and the harmonic content decreases with the increase of the number of times.

2. In the temperature control circuit of the boiler, with the increase of control angle $\alpha$, the content of each part is decreasing, but the content of fundamental wave is obviously faster than other harmonic velocity, so there will be a large number of harmonics.

3. Temperature Control Design of High Temperature Boiler Based on Three-Phase PWM Rectifier

In view of the serious harmonics caused by the traditional boiler temperature-controlled power supply mode, this paper proposes to use three-phase voltage-source PWM rectifier as the temperature-controlled power supply mode of high temperature boiler. Compared with the traditional power supply mode, three-phase voltage-source PWM rectifier consists of six fully controlled silicon controlled power devices with three arms, which can solve the problem of harmonic suppression and improve power factor through PI. The regulator output stable DC voltage, which lays a good foundation for boiler temperature control. The simulation results show that the scheme is feasible.

3.1 Working Principle of PWM Rectifier

PWM (Pulse Width Modulation) control is a pulse width modulation technology. It controls the DC output voltage by controlling the turn-on time of thyristor, and finally achieves temperature stability control. In a stable state, each phase arm of the rectifier bridge is driven by pulse width modulation according to sinusoidal law, which can output a relatively stable voltage output in the harsh environment of high temperature boiler temperature control. Figure 4 Topology diagram of three-phase PWM rectifier.

![Figure 4. Rectifier Topology](image)

3.2 Simulation analysis

In order to verify the feasibility of the scheme, this paper uses Simulink module in MATLAB simulation software to build a circuit model and carry out simulation research. The simulation parameters are inductance $L = 10\, \text{mH}$, line input equivalent resistance $R = 0.5\, \Omega$, DC side filter
capacitor \( C = 4700 \mu F \), AC side input phase voltage peak \( V = 100V \), DC side output voltage instruction 300V, PWM switching frequency set to 9K. When \( t = 0.8s \), an external interference is given. The simulation results (figure 5) show that the DC output voltage is very stable and the overshoot is small; even when the external conditions change, the whole system can quickly reaching stability after PI adjustment, and the time to reach stability is less, which indicates that the system has a good dynamic response; the input voltage and current waveforms on the grid side are shown in figure 6, and the waveforms of voltage and current in the same phase and current and voltage are distorted. It has low variable rate and high power factor.

![Figure 5. DC output voltage](image)

![Figure 6. Voltage and current waveforms of power grid](image)

4. Concluding remarks
Through the harmonic analysis of the traditional boiler temperature control circuit, it is found that the harmonic of the circuit is very large. In order to improve the harmonic content, the PWM rectifier circuit is adopted. The AC is converted to DC by the PWM rectifier circuit, and the DC output voltage is controlled to control the temperature. Compared with the traditional boiler AC voltage and temperature control, the circuit has better dynamic and static performance and higher power factor. The advantage of low harmonic content. The simulation results verify the feasibility and validity of the circuit in the boiler temperature control system. However, in practical applications, there may be some considerations such as heat dissipation design of the whole system, power loss of switching devices and so on. There will be many practical problems to be studied in depth.

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