Application of cascade PID plus feedforward in automatic denitration control

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Abstract. Generally, single PID loop plus feedforward control was adopted for the automatic denitration control in the power plant. When the ammonia pressure, unit load or NOx concentration of SCR inlet changes drastically, the adjustment control could not respond quickly, and the hysteresis is obvious. Based on the strategy of cascade PID plus feedforward control, a mathematical model for predicting the NOx concentration of the chimney inlet is constructed, which can reflect the boiler combustion conditions in real time. When the unit is in AGC-R mode, the feedforward control signals can be provided in time to adjust the ammonia injection flow, which can overcome the control problem caused by the characteristic of large hysteresis, and reduce the control overshoot and ammonia slip, and save the ammonia injection.

1. Introduction
In the context of the current large-scale grid connection of new energy in power industry, thermal power units frequently participate in peak shaving and the peaking depth is increasing. Therefore, the operating conditions of the boiler frequently change in a wide range, so that the flue gas parameters change frequently, including the NOx concentration of the SCR(Selective Catalytic Reduction) inlet.

SCR is currently the most widely used denitration method in thermal power plants. The principle of SCR denitration is to reduce NOx to N₂ by NH₃ under the action of catalyst. The main chemical reaction occurs as follows:

\[ 4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O \]

Nowadays, single PID loop plus feedforward control was adopted for automatic denitration control in the power plants. The PID loop regulates the NOx concentration of SCR reactor outlet, and the feedforward is generally the change rate of the unit load. In this control mode, the effect of automatic adjustment of denitration is poor. It is often necessary for the operators to intervene and manually adjust the flow of ammonia spray, resulting in large fluctuations in ammonia injection and large fluctuations in NOx concentration of SCR reactor outlet[1].

When the actual ammonia injection flow is less than the required by the working condition, the NOx emission concentration is likely to exceed the standard; when the actual ammonia injection flow exceeds the required by the working condition, the ammonia slip is high, which could aggravate the formation of NH₄HSO₄, and cause corrosion or blockage of the air preheater. Furthermore, as the denitration system is characterized of large hysteresis, non-linearity and time-varying, it is a very important research topic to optimize the adjustment of SCR denitration ammonia injection, and effectively control the NOx concentration of the chimney inlet.
2. The New Control Strategy of Denitration System

When the unit is in AGC-R mode, the unit load and the NOx concentration of SCR denitration inlet change drastically, and the NOx concentration of the chimney inlet is prone to oscillating divergence, which is difficult to control smoothly, and human intervention is needed. This not only reduces the automation level of the auxiliary machine, but also increases the labour intensity of the operating personnel. The control strategy proposed in this paper could automatically adjust the ammonia injection and track the change of NOx concentration of the SCR reactor inlet in time, so that the NOx concentration of the chimney inlet remains stable.

The SAMA diagram of the optimized control strategy for denitration ammonia injection using cascade PID plus feedforward proposed in this paper is shown in Fig. 1.

![Fig.1 Control strategy for denitration system after optimization](image)

The main PID loop PID1 adjusts the NOx concentration of SCR outlet. The output of the main PID loop PID1 is corrected by a correction function to correct the theoretical ammonia injection flow, and the vice PID loop PID2 adjusts the ammonia supply flow. The output of the vice PID loop PID2 plus four feedforward is applied to the regulating valve to adjust the flow of ammonia injection.

Due to the inaccuracy of flue gas flow measurement, the theoretical ammonia flow is creatively calculated through the main steam flow, as shown in formula 1.

\[
Q = a \times (C_{in} - C_{out, set}) \times \left(\frac{Q_A + Q_B}{2}\right)
\]

Where: \(Q\) is the required ammonia flow for the unilateral denitration reactor, kg/h; \(C_{in}\) is the NOx concentration process value of SCR reactor inlet, mg/m\(^3\); \(C_{out, set}\) is the NOx concentration set value of SCR reactor outlet, mg/m\(^3\); \(Q_A\), \(Q_B\) are the main steam flow of A side and B side of the boiler respectively, t/h; \(a\) is the coefficient, calculated according to the designed flue gas flow, main steam flow, NO\(_2\) molar mass and NH\(_3\) molar mass under the unit rated load.
The output of the main PID loop PID1 is multiplied by the theoretical ammonia injection flow after the correction function f1(x), that is, the theoretical ammonia injection flow is corrected. The correction coefficient range is a-b, a<b. The corrected theoretical ammonia injection flow is applied to the adder Σ 1, and then is added to the manual offset flow of the operator to obtain the actual required ammonia injection flow. According to the operating conditions of the unit, the actual required ammonia injection flow is multiplied by the coefficient B, which is the set value of the vice PID PID2 after the standardization process. The actual measured ammonia gas flow is also multiplied by the coefficient B, which is the process value of the vice PID PID2 after the standardization process. The vice PID loop PID2 uses negative action, proportional and integral operation[2-3].

By communicating with the operating personnel and analyzing the historical data of the unit, it is found that in most cases, the SCR reactor inlet NOx concentration will decrease as the unit load increases, and will increase as the unit load decreases. Therefore, considering the vast majority of cases, the slope of the function f2(x) is negative.

The CEMS device is purged once every hour. During the purge, the SCR reactor inlet NOx concentration and the SCR reactor outlet NOx concentration remain unchanged, and the main PID loop PID1 is no longer adjusted, and the feedforward 1 and feedforward 3 are maintained. In the process, if there is combustion adjustment, coal quality change, load change or start-stop coal-mill, it is easy to cause the SCR reactor outlet NOx concentration and the chimney inlet NOx concentration to exceed the standard. Therefore, during the CEMS purge, the desulfurization outlet NOx concentration is involved in the adjustment. A switching block is disposed in the feedforward 4. During the CEMS purge, the desulfurization outlet NOx concentration is involved in the adjustment, and when the CEMS purge is completed, the adjustment effect of desulfurization outlet NOx concentration is reduced to zero.

The output of the vice PID loop PID2 plus 4 feedforward is superimposed on the adder Σ 4, and then acts on the ammonia injection regulating valve after the limiting module to adjust the ammonia injection flow and control the SCR reactor outlet NOx concentration and the chimney inlet NOx concentration. The limited range is determined based on the actual operating conditions of the unit and the experience of operating personnel[4].

3. The Practical Application of Control Strategy

The following is a detailed description of the implementation and application of the control strategy with a 335 MW unit as an example.

The SAMA diagram of the automatic control strategy for denitration before optimization is shown in Fig. 2. The original control strategy is based on single PID plus feedforward, and the PID regulates the SCR reactor outlet NOx concentration.

![Fig.2 Control strategy for denitration system before optimization](image-url)
Before optimization, the automatic adjustment effect of denitration is shown in Fig. 3(a). The NOx concentration of A-side SCR reactor outlet is controlled within the set value ±15.

![Fig. 3](image)

When the denitration facility is purged, the NOx concentration of A and B side SCR reactors outlet is controlled within the set value ±25, and sometimes even the overshoot is greater.

Use the control strategy proposed in this paper to optimize as follows.

In formula (1), it is calculated according to the flue gas rate flow, the main steam rate flow, the NO2 molar mass, and the NH3 molar mass under the rated unit load, and then a equals 0.0004.

The correction function f1(x) in Fig. 1 is set as follows.

| x  | 0   | 50  | 100 |
|----|-----|-----|-----|
| f1(x) | 0.6 | 1   | 1.7 |

The output range of the correction function f1(x) is 0.6-1.7. The corrected theoretical ammonia injection flow is added to the adder Σ 1, and the manual offset is also added to the adder Σ 1 to obtain the actual required ammonia flow. According to the operating conditions of the unit, the actual required ammonia flow is multiplied by the coefficient B, that is, the standardization process is performed, as the set value of the vice PID PID2. The coefficient B is set to 0.8, and the proportional band is set to 230, and the integration time is set to 1.2 min in the example.

The function f2(x) in Fig. 1 is set as follows:

| x  | -120 | -2  | 2   | 120 |
|----|------|-----|-----|-----|
| f2(x) | -95  | 0   | 0   | 95  |

The function f3(x) in Fig. 1 is set as follows:

| x  | -50 | -2  | 2   | 50  |
|----|-----|-----|-----|-----|
| f3(x) | 15  | 0   | 0   | -25 |

The function f4(x) in Fig. 1 is set as follows:

| x  | -50 | -3  | 3   | 50  | 100 |
|----|-----|-----|-----|-----|-----|
| f4(x) | -20 | 0   | 0   | 20  | 40  |
The function $f_5(x)$ in Fig. 1 is set as follows:

| $x$  | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 60 | 85 |
|------|----|----|----|----|----|----|----|----|----|
| $f_5(x)$ | -8 | -5 | -2.5 | 0 | 5 | 10 | 15 | 25 | 25 |

After optimization, when the unit is in AGC-O mode, the NOx concentration of A-side SCR reactor outlet could be controlled within the set value ±10 and the automatic adjustment effect of denitrification is shown in Fig. 3(b). The NOx concentration set value of SCR reactor outlet was subjected to a positive +10 step disturbance test after optimization and the adjustment effect is shown in Fig. 4. The parameters change smoothly, and the NOx concentration of SCR reactor outlet could quickly reach the set value.

![Fig. 4 NOx concentration set value +10 step disturbance test](image)

After optimization, when the unit is in AGC-R mode, the unit load and the NOx concentration of SCR reactor inlet change drastically, and the control strategy could automatically adjust the ammonia injection flow to track the change of the NOx concentration in time. The adjustment effect of NOx concentration of the chimney inlet is shown in Fig. 5[5-6].

![Fig. 5 NOx concentration of chimney inlet in AGC-R mode](image)

From Fig. 5, it can be seen that the NOx concentration of the chimney inlet fluctuates between 30 mg/m³ and 46 mg/m³ in the three hours from 02:10 to 05:10, which meets the requirements for ultra-low emission of the unit.
4. Conclusion
Compared with the existing control technology, this paper proposes a mathematical model for predicting the NOx concentration of the chimney inlet based on the cascaded PID plus feedforward.

It can reflect the combustion conditions of the boiler in real time, and provide feedforward control signals in time, and adjust the ammonia injection flow. So it could overcome the control problems caused by the characteristics of hysteresis of the denitration system, and reduce the control overshoot, and save the ammonia injection flow, which could reduce ammonia slip and enable accurate control of ammonia injection.

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