Flexible Control of Wet Desulphurization Process Based on Frequency Retrofit

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Abstract. To assist in the absorption of renewable energy, coal-fired power plants need to operate over a wide range of loads, which exacerbates the challenge of the time delay in the wet desulphurization process. Therefore, this paper proposes a new control structure based on frequency retrofit and a corresponding model predictive controller to change the traditional idea of wet desulphurization control. This structure provides faster control actions, thus reducing time delay directly. And it makes the original discrete control variable continuous, enabling most control methods. The field application to the wet flue gas desulphurization system reveals the practical prospects of the proposed control structure and simulations have been conducted to verify the merits of the proposed control scheme based on data collected from a 1000 MW power plant.

1. Introduction

In recent year, emissions of sulphur dioxide have received much attention for environmental reasons. As a major thermal power producer, Chinese government has implemented the Ultra-low Emission Standard and is making significant efforts to develop renewable energy sources. Restrictions on sulphur dioxide export concentration and the large load changes associated with absorbing renewable energy are creating greater challenges for wet desulphurization process control.

Considering that the limestone-gypsum wet flue gas desulphurization (WFGD) has a world market share of 85% and a Chinese market share of over 90% [1], many studies on this industrial process have been broadly investigated. But giving a closer review on these studies, e.g. [2-6], it shows that the core of most control schemes still lays on pH value [7], which is normally controlled by the inlet flow of limestone slurry. It is difficult to satisfy the demands of both the pH value and the final desired outlet concentration of sulphur dioxide by relying only on the fresh limestone slurry flow. And considering the wide range of load changes caused by absorbing renewable energy generation, the wet desulphurization system usually needs to operate with a higher power to cover its slow actions. Both the control performance and the high energy consumption problems are to some extent due to the lack of space for control.

Motivated by the statements above, this paper attempts to develop a new control structure and a corresponding model predictive controller of the wet desulphurization process control based on frequency retrofit. By applying the variable frequency recirculated slurry pump, the frequency can provide faster control actions and the control target can be switched to the original desired one, the sulphur dioxide outlet concentration, thus improving control performance. Physical experiments have verified the feasibility of the scheme and its effectiveness in energy consumption reduction. Considering the physical limits and the innate abilities of MPC in handling constraints, a model predictive controller is adopted to achieve expected performance.

The remainder of this paper is organized as follow. Section 2 describes the proposed control structure of wet desulphurization process. Section 3 shows the design of the corresponding model predictive controller. Section 4 presents the field application and the simulations. Finally, Section 5 summarize the article.

2. Wet Desulphurization Process with Frequency Retrofit

2.1. System description

The physical structure of the WFGD system is shown in figure 1. The incoming raw flue gas from the dry precipitator passes the induced draft fan into the gas-gas heat exchanger to release its energy. Then it enters the desulphurization tower through the booster fan. In the meantime, fresh limestone slurry is produced and sent to the recirculated slurry tank.

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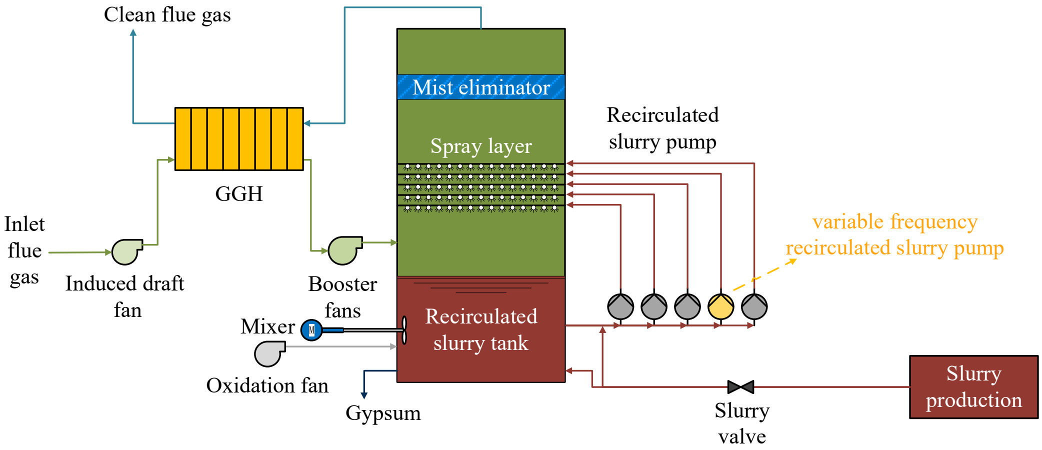


Figure 1. Wet Desulphurization System.

In the tower, the fresh limestone slurry is mixed with the slurry in the tank to regulate the pH value of the recirculated slurry. Through recirculated slurry pumps, the recirculated slurry is brought to the spray layer and sprayed down as droplets. The $CaCO_3$ in these droplets reacts with the sulphur dioxide when the droplets meet the raw flue gas flowing upward. This reaction produces $CaSO_3$, which will be oxidized to $CaSO_4$ by the oxidation fan. The chemical reactions are shown below.

Table 1. Chemical Reactions of Wet Desulphurization Process.

Stages	Reactions
Hydrolysis:	$SO_2 + H_2O \Leftrightarrow H^+ + HSO_3^-$ $HSO_3^- \Leftrightarrow H^+ + SO_3^{2-}$
Dissolution:	$CaCO_3 + H^+ \Leftrightarrow Ca^{2+} + HCO_3^-$
Oxidation:	$2HSO_3^- + O_2 \Leftrightarrow 2SO_4^{2-} + 2H^+$
Crystallization:	$Ca^{2+} + SO_4^{2-} + 2H_2O \Leftrightarrow CaSO_4 \bullet 2H_2O$

The $CaSO_4 \bullet 2H_2O$ can be discharged from the tower and processed into gypsum products, while the purified flue gas is released into the atmosphere after passing via the mist eliminator and heat exchanger.

It should be noted that one of the recirculated slurry pumps is modified with a frequency converter and becomes variable frequency recirculated slurry pump. Unlike the original ones, it can be seen as a continuous control variable, which can be regulated by controller automatically.

2.2. Control Structure Based on Frequency Retrofit

Traditionally, the control variables are the inlet flow of limestone slurry which has been widely discussed in control field, and the combinations of recirculated slurry pumps which are normally controlled manually for safety reasons. And the traditional control schemes centred on pH value are difficult to tune well when the system faces large load changes because the control action has to wait for the chemical process to finish before it can present its effect. Moreover, even if the effect has taken place, it still can not be detected until the flue gas flow to the outlet of the desulphurization tower.

However, after applying the frequency retrofit on the recirculated slurry pump, the frequency can be an additional control variable, which can provide more direct control actions theoretically and spatially. The control structure is illustrated in figure 2, where the shaded part is exactly what this paper is interested in.

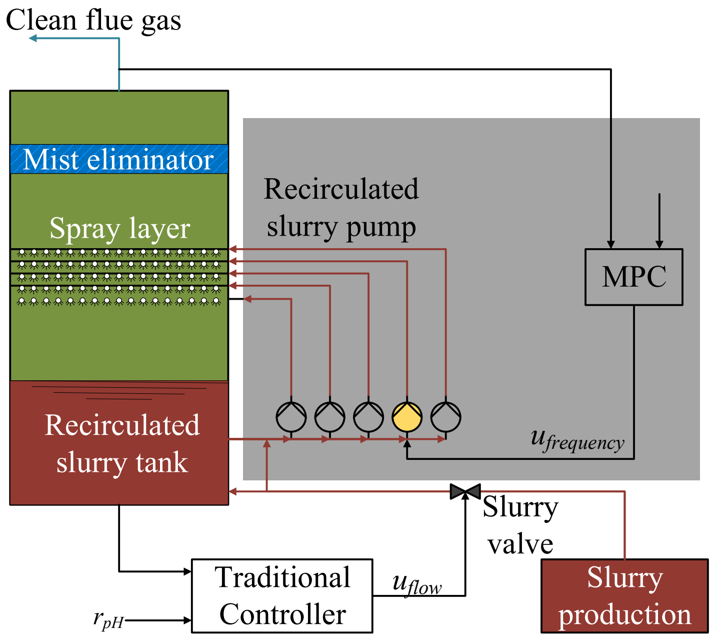


Figure 2. Control Structure.

As can been seen in figure 2, this scheme provides a decoupling way to achieve flexible control structure. The classic pH-centred controller is retained, but it now only needs to be concerned with keeping the pH value stable, which can be regulated slowly and gradually in this scenario. And the model predictive controller will provide timely control action to achieve a satisfactory control performance.

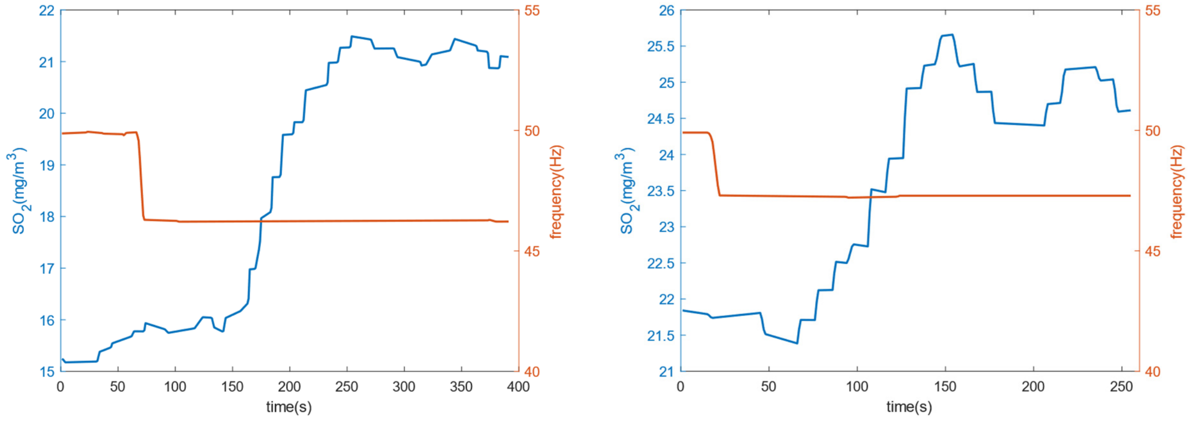
2.3. Dynamic Behaviors

In order to obtain the system model, step experiments are conducted on a 1000 MW power plant in Taizhou No.2 power station. Giving several step signals to the variable frequency recirculated slurry pump manually, the outlet sulphur dioxide concentration changes can be detected and recorded, which is used to establish the model later. Figure 3 shows the step experiments.

Under different load levels, the step responses show a similar pattern that once the frequency changes, the outlet sulphur dioxide concentration tends to move in the opposite direction with a hysteresis and inertia. Based on the responds of these step experiments, this paper adopts the traditional inertial transfer function with time delay as the system model, which is commonly approved by many studies, such as [8, 9]. Due to properties shown in the curves, a first-order with time-delay transfer function is an appropriate model to describe the system dynamic. The specific form of the model is

$$G(s)=\frac{K}{1+Ts}e^{-Ls},(1)$$

where K is the process gain, T is time constant, L is time delay and s is Laplace operator.



(a). 650 MW. **(b).** 950MW.

Figure 3. Step Experiments.

After system identification, the obtained system parameters are $K=-1.4647$, $T=32.0513$, $L=91$, and the sampling time T_s is set to 1 second. The fit percent of this model is over 90%, which can be considered enough for the industrial process control. The result of the identification is shown in figure 4.

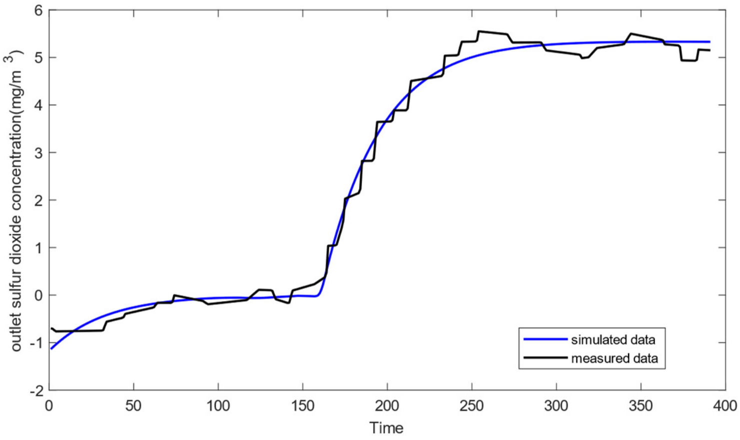


Figure 4. Model Identification Result

With the system model above, the basis for applying control methods to this new control structure is established. Since it is rarely explored, it still has much to be discovered.

3. Model Predictive Controller Design

Considering the physical limits commonly exist, a model predictive controller is adopted due to its natural ability of handling complex constraints [10-12]. And according to the basic idea of MPC, the controller design includes predictive model, objective function optimization, and rolling horizon control [13], which is shown in figure 5.

Generally, the model predictive controller needs a discrete-time form system model. According to equation (1), the discrete state space form of the model can be obtained through using the Laplace transformation and the Euler differential equation,

$$x(t+1)=(1-\frac{1}{T})x(t)+\frac{K}{T}u(t-L) \qquad (2)$$

where $x(t)\in \mathrm{R}^{n_x}$ is the outlet sulphur dioxide concentration at time t, n_x is the dimension of state variable, and $u(t)\in \mathrm{R}^{n_u}$ is the frequency of the variable frequency recirculated slurry pump at time t, n_u is the dimension of manipulated variable.

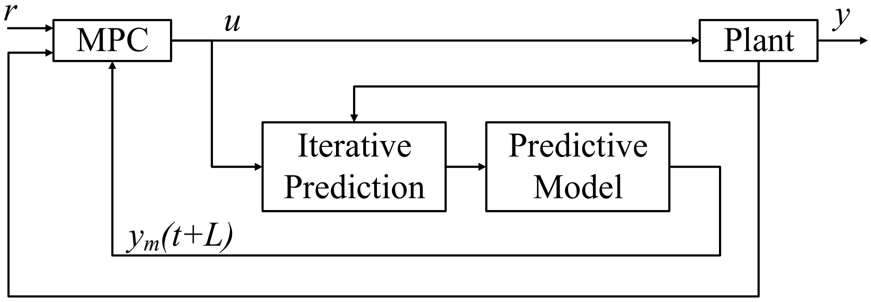


Figure 5. Model Predictive Controller Design

The large time delay in the process is treated by the innate characteristic of MPC, which uses the L-step-ahead prediction to compensate for the time delay [14]. Since the predictive model is known and the previous control sequences $[u(t-L),u(t-L+1),\cdots,u(t-1)]$ are known, the predictive output can be obtained,

$$x^{t+i+1}=(1-\frac{1}{T})x^{t+i}+\frac{K}{T}u(t-L+i). \qquad (i=0,1,\cdots,L) \qquad (3)$$

The future prediction x^{t+L} can therefore be used to design the current control variable $u(t)$. In order to achieve a stable control performance, the control law is set as:

$$u=K_{lqr}x+v, \qquad (4)$$

where K_{lqr} is the feedback gain, and v is optimized by MPC. In this paper, the Linear-Quadratic-Regulator method is used to calculate the K_{lqr}.

With the predictive model and the delay compensation, the model predictive controller can optimize the objective function and obtain the optimized control input in a rolling horizon approach, where only the first element is adopted. The MPC formulation is presented below.

$$\min_{v}\left\{c_f(x^N)+\sum_{i=0}^{L-1}c_1(x^i,u(i-L))+\sum_{i=L}^{N-1}c_2(x^i,u^{i-L})\right\},$$

$$s.t.\begin{cases} c_f(x^N)=(x^N)^T Q(x^N), \\ c_1(x^i,u(i-L))=(x^i)^T Q(x^i)+u(i-L)^T Ru(i-L), \\ c_2(x^i,u^{i-L})=(x^i)^T Q(x^i)+(u^{i-L})^T R(u^{i-L}), \\ u^i=K_{lqr}x^{i+L}+v, \\ x\in S^x \\ u\in S^u \end{cases} \tag{5}$$

where S^x is the state constraint set and the S^u is the input constraint set.

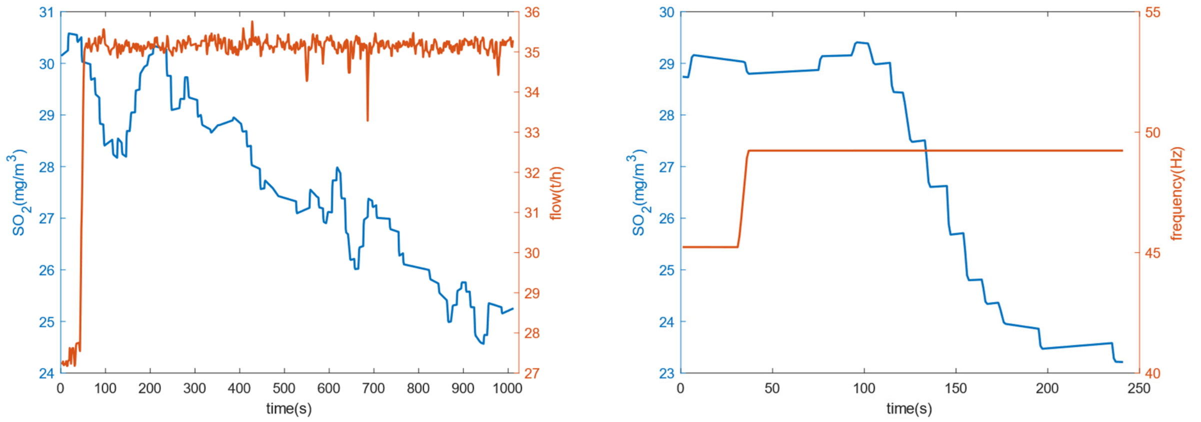
As can be seen in equation (5), at each predictive horizon, the formulation begins at $x(t)$, but the actual optimization starts at x^{t+L+1}, and the sum of c_1 is actually a constant term. The given MPC formulation can be solved to a local optimum by many methods, and in this paper, IPOPT is used to solve such a problem.

4. Experiments

In this section, two cases have been presented to demonstrate the effect of the proposed scheme, and they share the same constraints. According to the Ultra-low Emission Standard, the outlet sulphur dioxide concentration should be less than 35 mg/m^3, and a tighter one, $0\leq x\leq 30$, is adopted here. Based on the physical experiments, the variable frequency recirculated slurry pump needs to work between 40-50 Hz, which is the input constraint.

4.1. Application to Wet Desulphurization Process

The first case is the field application of the new control structure on a real WFGD system. By step experiments under a 800 MW load, the comparison of the proposed control structure and the original one shows the merits of this idea.



(a). pH-centred control structure. **(b).** flexible control structure.

Figure 6. Comparison of Two Control Structure.

The pH-centred control structure is the traditional control scheme, whose actual control variable is the fresh limestone slurry flow. And the flexible control structure is the proposed one, which use the frequency of the recirculated pump to regulate the outlet concentration of sulphur dioxide. Figure 6 shows that the frequency-associated control structure can achieve stable faster than the traditional one by minutes. And the curve of the outlet sulphur dioxide concentration of the proposed one is also better with less oscillation, which might owe to the spatially closer distance of the actuator from the sensor of the proposed structure.

4.2. Simulation and Analysis

The merits of applying the flexible control structure has shown, and it will need a controller to realize its potential. Since proportional-integral-derivative (PID) is commonly applied in industrial systems, it is also introduced to be the standard to evaluate other controllers. The specific form the PID controller is:

$$G_{PID}(s)=K_P+K_I\frac{1}{s}+K_D\frac{K_N}{1+K_N\frac{1}{s}}, \tag{6}$$

where $K_P=-0.3206$, $K_I=-0.004638$, $K_D=9.8930$, and K_N=0.007657.

Reviewing equation (5), the weight matrixes are parameters that need to be tuned. Since the system here has a one-dimension state variable and a one-dimension control variable, which means $Q\in\mathrm{R}$ and $R\in\mathrm{R}$, the weight matrixes will be easy to find an acceptable choice. In this paper, the weight matrixes are set to $Q=5$, and $R=0.01$ to balance the tracking ability and the robustness. Figure 7 shows the control performances of the controllers.

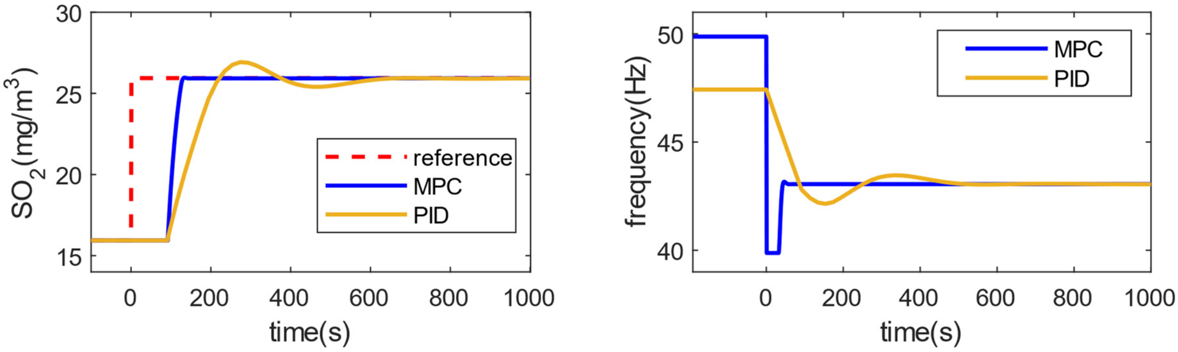


Figure 7. Performances of the Controllers on the Pump.

As can be seen from figure 7, compared to PID controller, MPC has hardly overshoot and needs less time to reach the target in this situation. It should be noted that PID is also sufficiently capable to perform this task, but the large time delay in the system may make it difficult for the PID controller to be well tuned.

Overall, the results demonstrate that the presented frequency-associated control structure of WFGD system can greatly improve control performance in industrial implementation. Although it is not a fully mature approach, it will offer a promising direction for better wet desulphurization process control.

5. Conclusions

This paper investigates the design of wet flue gas desulphurization process control, which traditionally is a pH-dependent indirect control. By introducing frequency retrofit to the recirculated slurry pump, a direct frequency-associated control structure is given, which can decouple the tangle situation between variables and reduce the time delay significantly. A model predictive controller for the time-delay system is designed to perform the control tasks. To demonstrate the effect of proposed configuration, a field application and a simulation is given to show the merits.

Overall, the flexible control structure of the wet desulphurization process can achieve better control performance than the original one, which is a promising scheme that offers environmental benefits with low energy consumption.

Acknowledgments

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