Optimization of back pressure control of direct air-cooling unit based on GPC

Jianyun Bai, Ru Shao¹ and Qi Ren
Department of Automation, Shanxi University, Taiyuan 030013, China

¹ Email:15735104851@163.com

Abstract. In view of the fact that the actual back pressure is difficult to track the set value quickly and stably, this paper applies the predictive control algorithm (GPC) which can respond quickly, has good robustness and is easy to realize in the industrial production site to optimize the back pressure control. The control performance of the back pressure control system with PID, fuzzy PID and GPC is compared and analyzed through the simulation test. The simulation results show that the GPC algorithm has better dynamic performance than PID and fuzzy PID control in the case of set point disturbance and internal disturbance, and has stronger robustness in the face of model mismatch. To sum up, GPC algorithm is more suitable for the back pressure control system under complex working conditions, and the optimization control method has a certain guiding significance for the actual production site back pressure control strategy improvement.

1. Introduction
In thermal power generation, the direct air cooling unit refers to the unit in which the axial flow cooling fan installed on the air cooling island uses air to cool the exhaust steam from the low pressure cylinder of the steam turbine and condenses the exhaust steam into water. The back pressure refers to the exhaust pressure of the steam turbine. The change of the back pressure will inevitably affect the output of the unit, so the control performance of the back pressure is directly related to the economic performance of the unit. At the same time, the current vigorous development and grid connection of new energy sources requires that thermal power units have better Automatic Generation Control(AGC) adjustment performance, which also brings new challenges to the control of the unit's back pressure.

In the actual production process, the back pressure control usually adopts the conventional PID control, but it has the problems of long adjustment time and poor anti-interference. It is difficult to quickly track the back pressure to the set value when the unit is changed to the working condition, so the engineer wants to find an intelligent algorithm that can respond quickly, has good model adaptability, and is easy to implement at the production site to optimize backpressure control. Due to the time-varying, non-linear and large hysteresis characteristics of the back pressure control object itself, it is difficult to establish an accurate mathematical model, and online model identification is also limited by the Distributed Control System(DCS) is not open and freely programmable area, it is difficult to apply to the actual production site, so urgent It is necessary to find a control algorithm with low model accuracy requirements and good adaptability to variable operating conditions to achieve fast and stable adjustment of back pressure, so as to reduce the standard coal consumption of power generation and improve economic efficiency. In this paper, the generalized predictive control is applied to the back pressure control system, relying on the good control performance and strong
robustness of GPC to quickly adjust the back pressure and improve the stability of the unit during operation.

2. Introduction to generalized predictive control

GPC is based on the principle of predictive control, adaptive control algorithm in conjunction with a control formation, was first proposed by Clarke et al [1].

After the GPC is pushed down and transformed by the formula, the principle diagram of Figure 1 can be obtained. It can be seen from the figure that GPC can be divided into three parts, namely softening, adjustment and prediction, and the thicker arrow flow represents a vector, and the thinner arrow flow represents a scalar. The specific process is: ① softening, the input \( y_r \) is softened to form the reference trajectory \( W \), which is the expected value vector of the system; ② adjustment, after calculating the difference with the predicted output and performing a dot product operation with \( g^T \) to obtain the control increment \( \Delta u(k) \); ③ Prediction, \( \Delta u(k) \) on the one hand gets \( u(k) \) through the integral operation, and acts on the control object, on the other hand returns to the system through the vector \( H \), and continues to predict the output.

![Figure 1. GPC control structure.](image)

As one of the representative algorithms of predictive control, GPC is also composed of the following three aspects:

2.1. Forecasting model

In all predictive control, there must be a basic model through which the output of the future moment can be predicted. It is precisely because of the prediction function of the model that any control strategy can be input according to the dynamic behavior of the system when controlling the actual object, and the advantages and disadvantages of the control strategy can be compared. GPC is an algorithm based on CARIMA, and the integral function of the model can be used to eliminate the residual error and enhance the steady-state performance of the system [2]. The model expression is as follows:

\[
A(z^{-1})y(k) = B(z^{-1})u(k-1) + C(z^{-1})\xi(k)/\Delta \tag{1}
\]

Among them, \( A(z^{-1}) \), \( B(z^{-1}) \) and \( C(z^{-1}) \) are respectively expressed as follows:

\[
A(z^{-1}) = 1 + \sum_{i=1}^{n} a_i z^{-i} = 1 + a_1 z^{-1} + \cdots + a_n z^{-n} \quad B(z^{-1}) = \sum_{i=0}^{d} b_i z^{-i} = b_0 + b_1 z^{-1} + \cdots + b_d z^{-d}
\]

In the formula, \( \Delta=1-z^{-1} \) denotes the difference operator, \( z^{-1} \) denotes the backward shift operator, and \( \xi(k) \) — white noise with zero mean. It should be noted that if the delay \( \tau \) of the selected object is greater than 1, the first item \( d-1 \) in \( B(z^{-1}) \) needs to be set to zero, that is, \( b_0 \sim b_{d-1} \). For the convenience of later calculation, it is generally assumed that \( C(z^{-1}) = 1 \).
2.2. Rolling optimization

(1) Objective function

In order to keep good control performance when the algorithm model is mismatched in GPC, the function of $u(k)$ at the current time is added to the index. The specific formula is as follows:

$$J = \sum_{j=1}^{N} [y(k + j) - w(k + j)]^2 + \sum_{j=1}^{M} \lambda(j) [\Delta u(k + j - 1)]^2$$  \hspace{1cm} (2)

In the formula, $N$ - maximum prediction length; $M$ - control length, $M \leq N$; $\lambda(j)$ - control weighting coefficient, which is generally a fixed value $\lambda$.

The addition of the latter part of the above formula avoids the surge of control function of the system and ensures the stable operation of the system. In most systems, the control function is to track the output $y_r$, but due to the introduction of the softening coefficient $\alpha$, the input is first softened to form a reference trajectory $w(k+j)$, and the control purpose is also changed to approach the output to the reference trajectory, that is, $y(k+j) \rightarrow w(k+j)$. The formula of $w(k+j)$ is as follows:

$$w(k + j) = \alpha^j y(k) + (1 - \alpha^j)y_r$$  \hspace{1cm} (3)

(2) Predictive output

In predictive control, it is necessary to predict the $j$-step output ahead of time, so the Diophantine equation is introduced [3].

$$1 = E_j(z^{-1}) A(z^{-1}) + z^{-j} F_j(z^{-1})$$  \hspace{1cm} (4)

Among them, $E_j(z^{-1})$ and $F_j(z^{-1})$ are respectively as follows:

$$E_j(z^{-1}) = e_{j0} + e_{j1} z^{-1} + \cdots + e_{jN_j} z^{-N_j}, \quad e_{j0} = 1 \quad F_j(z^{-1}) = f_{j0} + f_{j1} z^{-1} + \cdots + f_{jN_j} z^{-N_j}$$

After multiplying the left and right sides of formula (2) by $E_j(z^{-1}) \Delta$, the joint formula (4) can be obtained:

$$y(k + j) = E_j(z^{-1}) B(z^{-1}) \Delta u(k + j - 1) + F_j(z^{-1}) y(k) + E_j(z^{-1}) \xi(k + j)$$  \hspace{1cm} (5)

Formula (5) represents the prediction equation of step $j$ after time $k$, and if $G_j(z^{-1}) = E_j(z^{-1}) B(z^{-1})$, the effect of noise can be ignored when predicting future output, then formula (5) can be abbreviated as:

$$\hat{Y} = G \Delta U + f$$  \hspace{1cm} (6)

In the formula, the expressions are as follows, $f$ is the open-loop prediction vector, $G_j(z^{-1})$ is the first $j$ term of the step response of the system $g_0, g_1, \ldots$:

$$\hat{Y} = [\hat{y}(k + 1), \hat{y}(k + 2), \ldots, \hat{y}(k + N)]^T$$  \hspace{1cm} (7)

$$\Delta U = [\Delta u(k), \Delta u(k + 1), \ldots, \Delta u(k + N - 1)]^T$$  \hspace{1cm} (8)

$$f = [f(k + 1), f(k + 2), \ldots, f(k + n)]^T$$  \hspace{1cm} (9)

$$G = \begin{bmatrix} g_0 & 0 \\ g_1 & 0 \\ \vdots & \vdots \\ g_{N-1} & g_{N-2} \end{bmatrix}$$  \hspace{1cm} (10)

(3) Optimal control rate

If $W=[w(k+1), w(k+2), \cdots w(k+n)]^T$ represents the softened reference trajectory vector, then the function $J$ can be rewritten into a formula (7):

$$J = (Y - W)^T (Y - W) + \lambda \Delta U^T \Delta U$$  \hspace{1cm} (11)
Replace \( Y \) in the formula with \( \hat{Y} \) after ignoring noise input, and obtain the minimum control increment \( \Delta U \) by finding that the partial derivative is equal to zero, the formula is as follows:

\[
\Delta U = (G^T G + \lambda I)^{-1} G^T (W - f)
\]

When the system is running, only the first component of \( \Delta U \) is given to the prediction and control object part, such as formula (9):

\[
u(k) = u(k-1) + g^T (W - f)
\]

In the formula \( g^T \) is the first line of \( (G^T G + \lambda I)^{-1} G^T \).

Different from the common control strategy, the function \( J \) of GPC in the system operation is not immutable, and the system will optimize it through on-line calculation.

2.3. Forecasting model
Different from other predictive controls, GPC does not have a clear feedback correction, but the function of feedback correction has been reflected in the first two parts during the operation of the system. When there is a deviation between the predicted output and \( y \), the model will be constantly modified and new optimization will be produced, which will eliminate the influence of interference in time when the system is faced with interference, so that the system has good robustness.

3. Back pressure model
After consulting the literature, the model obtained by scholars using the fan speed increase of 10% as the step disturbance test input under three typical working conditions is used as the back pressure object model of this simulation study [4].

The second-order inertia delay link is adopted in the model, which can include more information in the back pressure control, and the established model is more accurate and closer to the object characteristics of the actual production site. Table 1 lists the specific transfer functions of the back pressure model under different loads.

| Typical load condition | Back pressure transfer function model |
|------------------------|--------------------------------------|
| 170 MW                 | \( g(s) = \frac{-19.4}{(170.2s + 1)(278.1s + 1)} e^{-31.2s} \) |
| 260 MW                 | \( g(s) = \frac{-17.8}{(150.6s + 1)(277.7s + 1)} e^{-53.5s} \) |
| 300 MW                 | \( g(s) = \frac{-16.6}{(145.7s + 1)(282.6s + 1)} e^{-18.5s} \) |

4. Simulation study on parameter selection of GPC controller
(1) Predictive time domain \( N \)
The prediction time domain is divided into minimum prediction time domain \( N_0 \) and maximum prediction time domain \( N_l \). The principle of GPC requires \( N_0 > d \) (delay). Taking the backpressure model under 170MW load as an example, we can set that \( N_0 = 32 \) s (\( N \) can only be taken as integers). When selecting \( N_0 \), it is required to include the response with more influence in the current control. If the \( N_0 \) selection is small, the system can respond quickly, but the robustness is poor. At the same time, the \( N_l \) selection will make the response speed of the system slower, so generally take the value of \( N_l \) as the rise time of the system, so choose \( N_l = 40 \) s.

(2) Control time domain \( M \)
The control time domain \( M \) is related to the tracking performance of the system, usually the larger \( M \) is, the better the tracking effect is, but at the same time, the overshoot of the system increases because of the multi-step prediction, which affects the stability of the system to a certain extent. When \( M \) is small, the number of columns of the \( G \) matrix of the system is reduced, the amount of calculation
is reduced, and the running time of the system program is reduced. At the same time, the output of the system is relatively smooth, and the control performance is improved. Therefore, for the low-order model, $M = 1$ can be selected to ensure the dynamic performance of the system without losing too much response speed.

(3) Weighting coefficient $\lambda$

The introduction of the parameter $\lambda$ is mainly used to reduce the system oscillation caused by the input surge of the controlled object by limiting the change of $\Delta u(k)$ when the system $\Delta u(k)$ surges. The increase of $\lambda$ can improve the stability of the system, but the $\Delta u(k)$ decreases accordingly, which makes the system regulation cannot achieve fast tracking, the response speed becomes slower, and the dynamic performance decreases.

When debugging the designed system, we can first set $\lambda$ to 0 (at this time $\Delta u(k)$ is not constrained) or a smaller number, and the value range is $0 < \lambda < 1$. By slowly increasing the value of $\lambda$ to find the optimal value, the system is stable and will not degrade the dynamic performance of the system because $\Delta u(k)$ is too low. Through the simulation software to change the $\lambda$ parameter of the GPC control system, the results show that the system adjustment time and overshoot decrease slightly with the increase of $\lambda$, but the response speed of the system becomes worse, which shows that the rise time and peak time increase, and cannot be tracked quickly after the increase of $\lambda$, so that the dynamic performance decreases instead of increasing. When $\lambda < 0.3$, the response curve of the system is basically unchanged. In order to ensure that the system has strong adaptability when the back pressure fluctuates frequently and $\Delta u(k)$ changes violently, $\lambda \geq 0.3$ is generally selected. To sum up, through software simulation and analysis, $\lambda = 0.3$ is selected as the best value.

(4) Softening factor $\alpha$

In the principle analysis, it is deduced that the system output $y(k)$ does not track $y_r$ directly, but indirectly tracks $y_r$ along $w$. It can be seen from the formula (3) that when the setting parameter $\alpha$ is small, the proportion of $y(k)$ is smaller, $w$ will approach $y_r$ more quickly, and the response speed of the system will be relatively faster, but it is difficult to maintain good robustness when the interference input is input; when the setting parameter $\alpha$ is large, because the proportion of $y_r$ decreases, the response speed of the system must be relatively slow, but the robustness will be improved. Therefore, when the control system is running, choosing the appropriate $\alpha$ will make the system still have good robustness while maintaining a relatively fast response speed.

Because the $\alpha$ parameter is related to the robustness of the designed system, $\alpha = 0.18$ is selected after simulation. Under this parameter, the dynamic performance of the GPC system designed under different back pressure models can meet the requirements of on-site back pressure control.

5. Simulation test and result analysis

After compiling the simulation program of MATLAB software, the GPC algorithm is applied to the back pressure control system of the unit, and the control performance of GPC back pressure control strategy is analyzed under model adaptation and model mismatch respectively, and compared with PID and Fuzzy-PID control strategy [5, 6, 7].

5.1. Simulation analysis of GPC control performance under model adaptation

In order to adapt to the situation that the setting value of back pressure may change continuously under complex working conditions in the field, taking 170MW load as an example, the influence of continuous step input disturbance on the system is analyzed, and the step setting input is [3 1 4 2 1]. The control effect comparison curve is shown in Figure 2.

As can be seen from Figure 2, in the face of continuous step input disturbance, the PID control cannot respond quickly, resulting in poor effect of system output tracking set value and long fluctuation time. The effect of GPC control system is better than that of PID and Fuzzy-PID control. Its shorter rise time and adjustment time enable the system to quickly track the set value in the case of continuous step input disturbance, and can realize the fast and stable control of the back pressure of the unit.
5.2. Simulation analysis of GPC control performance under model mismatch

(1) Variable load condition

In order to verify the robustness of the designed system under variable load conditions, the GPC control system designed with 170MW back pressure model is used to control the other two operating conditions. Because the predicted time domain $N$ of the system designed at 170MW load is large, the responses with more influence in the current control can be included. The specific simulation curve is shown in Figure 3.

It can be seen from Figure 3 that the system can achieve fast and stable control under 170MW load. When the system model parameters are changed to 260MW back pressure model, the response speed of the system decreases slightly, but the adjustment time is consistent with 170MW, and its dynamic performance meets the control requirements as a whole. Under the load condition of 260MW, because the set prediction time domain $N_l$ is larger than the actual maximum prediction time domain $N$, the rise time and adjustment time increase, and the system response speed decreases, but it is still much lower than the traditional PID control and Fuzzy-PID control. It is proved that the back pressure control system using GPC algorithm can maintain good stability and dynamic performance in the face of model mismatch under load conditions. Its robustness can meet the requirements of on-site back pressure control.

(2) Random noise interference

The step input of the set value input of 15 to 20 is used to simulate the setting range of the back pressure value. At the same time, the noise disturbance input with variance 0.1 is added to the controlled object, and the output curves of the system under PID and GPC control strategies are observed, and the control effect is analyzed. The simulation results are shown in Figure 4.

As can be seen from Figure 4, when using PID control, the system fluctuates greatly under the interference of noise, and the set value cannot be tracked stably in the simulation time, which is bound to cause frequent fluctuations of back pressure on the site and threaten the safety of the unit. After using GPC control, the output of the system basically fluctuates within a certain range of the set value, and the system shows strong robustness.

(3) Change the model parameters

Taking 170MW as an example, the model mismatch caused by environmental factors and unit operation condition is simulated by increasing and decreasing the model parameters by 20% respectively. At the same time, according to the operator's experience, it is generally difficult to control the model mismatch when $K$ increases, $T$ decreases and $\tau$ increases. Therefore, the $K$ and $\tau$ of
the model object under 170MW load are increased by 20%. At the same time, the reduction of $T$ by 20% is regarded as one of the typical working conditions of model mismatch. The specific simulation results are shown in Figure 5-Figure 7.

![Figure 4](image1.png)  ![Figure 5](image2.png)

**Figure 4.** Response curve of GPC back pressure control system under random noise interference. **Figure 5.** Model parameters increase by 20%.

As can be seen from Figure 5, when the model parameters are adjusted, the oscillation of the output curve of the control system is intensified, and the oscillation of the output curve of the control system is intensified under either the set value disturbance or the internal disturbance input of PID and Fuzzy-PID control, and the adjustment time is longer than that under the model adaptation, and the dynamic performance of the system decreases. With the increase of $\tau$ parameter in GPC control system, the minimum predictive time domain $N_o$ set by the system is lower than $\tau$ value, and the predictive time domain $N$ is lower than the optimal value, which prolongs the adjustment time and decreases the dynamic performance of the system slightly. But compared with PID and Fuzzy-PID control, the control performance is the best in the case of set value disturbance and internal disturbance, which can track the set value faster, show good anti-jamming ability, and the system is more robust.

![Figure 6](image3.png)  ![Figure 7](image4.png)

**Figure 6.** Model parameters reduced by 20%. **Figure 7.** Model parameters $K, \tau$ increase by 20%, $T$ decrease by 20%. 
As can be seen from Figure 6, when the model parameters decrease, the control effects of the three controllers are improved, the system output overshoot is reduced, and the adjustment time is greatly reduced. In the face of internal disturbance, the GPC control system also shows a strong tracking ability, which can be quickly adjusted to the steady state value.

As can be seen from Figure 7, when the model parameters $K$ and $\tau$ increase by 20% and $T$ decreases by 20%, the dynamic performance of GPC and Fuzzy-PID control strategies is improved under the disturbance of the set value, and the overshoot and adjustment time of both are greatly reduced, while the output oscillation of traditional PID control is serious. When the internal disturbance is input, the output fluctuation amplitude of the system with GPC control strategy is the smallest, which can recover to the steady state value of the system more quickly.

To sum up, through the simulation experiments of the designed back pressure control system under the conditions of model adaptation and model mismatch, it is concluded that the response speed of GPC control strategy is faster in the case of set value disturbance and internal disturbance, and can be quickly adjusted to the steady state value in the face of internal disturbance, and its dynamic performance is relatively best. It shows good robustness in the face of model mismatch, and compared with PID and Fuzzy-PID control, it is more suitable for on-site back pressure control, which can meet the requirements of stable and fast back pressure control under different working conditions and influencing factors.

6. Conclusions
In this paper, according to the situation that it is difficult for the field back pressure control to track the set value quickly and stably, the GPC algorithm with fast response, good robustness and easy to be implemented in the industrial field is applied to optimize the back pressure control. The simulation analysis shows that under the condition of set value disturbance and internal disturbance, the GPC control strategy has faster response speed, stronger anti-interference ability, better dynamic performance and steady-state performance than PID and Fuzzy-PID control strategy, and shows good adaptability in the face of model mismatch, so it is more suitable to be applied to the back pressure control system running under complex operating conditions. It can realize the stable and rapid control of the back pressure under different working conditions, which has a certain guiding significance for the improvement of the back pressure control strategy.

References
[1] Liu X H 2011 D. Research on Control method of Ball system based on Predictive Control
[2] Li M W 2019 D. Time delay compensation and control of networked control systems based on generalized predictive control
[3] Wang H L 2014 D. Generalized Predictive Control based on support Vector Machine
[4] Qu Y 2019 D. Study on back pressure modeling and control strategy optimization of direct air cooling system
[5] Xin X G, Chen S H, Wang B, et al. 2016 J. Automation and Instrumentation 31(02) 37-41
[6] Wang Q, Wang L, Jing X, et al. 2018 J. Journal of Shanxi University (Natural Science Edition), 41(03) 527-532
[7] He T X, Du Y.2013 J. Computer Simulation 30(09) 391-393