Research on optimization of primary frequency regulation of thermal power units based on multi-model predictive control

Aimin Gao¹, Xiaobo Cui²³⁴, Guoqiang Yu¹, Jianjun Shu¹, Xiaolong Yang¹ and Tianhai Zhang¹

¹ Jiangsu Frontier Electric Technology Co., Ltd, Nanjing 211102, China; ² School of Energy and Power Engineering, Nanjing Institute of Technology, Nanjing 211167, China; ³ School of Energy and Environment, Southeast University, Nanjing 210096, China

⁴ Email: njit_xiaobo@163.com

Abstract. The nonlinear problem of system cannot be well solved using traditional power regulation system, which causes regulation lag and insufficient output and poor accuracy of the actual performance of the primary frequency regulation (PFR) on thermal power units. In order to further improve PFR performance of thermal power units, a multi-model predictive control method is adopted to optimize and improve the traditional steam turbine power control system. A PFR optimal control strategy is proposed, which improves the regulation performance and robustness of the power control system. The simulation results show that the proposed optimization algorithm can overcome the nonlinear problem of the steam turbine governing valve, and the regulating process is stable and fast without overshoot. This research is of great significance to improve the contribution rate of PFR of thermal power units and to better satisfy the assessment of power grid PFR, thereby to stabilize the frequency of power grid.

1. Introduction
At present, the access of new energy power generation into the grid is gradually increasing, and the proportion of new energy is steadily increasing. In order to improve the consumption of new energy power, the PFR performance of thermal power units is particularly important. However, in the actual process of PFR on thermal power units, the performance of PFR is not ideal, which is mainly manifested in problems such as insufficient frequency regulation output, poor frequency regulation accuracy and lag in regulation process [1-4].

With the gradual completion and operation of UHV transmission lines, accidents such as DC blocking and sudden loss of external power have occurred, and the impact on the receiving end power grid has become more and more serious, therefore the requirements for improving the PFR performance have become more and more urgent.

Before large-scale new energy is connected to the grid, it is of great significance to study the PFR optimization control strategy and to improve the PFR performance of thermal power units, in order to improve the frequency regulation performance and the ability to resist external disturbances of the grid.

The power regulation and control system of traditional thermal power unit is designed based on feedforward and PID feedback [5-6]. Since the power output of the steam turbine is determined by the valve opening of the turbine and the main steam pressure, this leads to the nonlinear flow characteristics of the power regulation system, leading to the problem of nonlinear flow characteristics.
of the power regulation system. However, traditional control methods cannot solve the problems above, and the control performance is not ideal. In addition, under different load conditions, power regulation process may have over- or under-regulation, and the regulation quality is obviously different [7-8].

In order to solve the above problems, firstly a multi-model predictive control strategy is proposed in this paper, then an improved power regulation control system is designed, and finally simulation comparison is performed between the improved PFR control scheme and traditional control methods in terms of PFR performance and system robustness.

2. Traditional power regulation
The typical power regulation system diagram of a thermal power unit is shown in Figure 1. The input of the controlled object is the comprehensive valve opening instruction of the controller, the instruction makes the actual valve opening reach \( \mu \) by manipulating the actuator \( G_Z \). The actual comprehensive valve opening is corrected by the main steam pressure \( P_T \) before the valve. Make the steam quantity into the turbine reach \( Q \), the steam flow through the steam turbine produces mechanical power \( P_m \), and mechanical power drives the generator to generate electricity power \( P_E \). The transfer function model of the steam turbine is \( G_T \), and the transfer function model of the generator is \( G_E \).

The calculation of the comprehensive valve opening instruction is based on the feedforward + feedback control structure. The basic PID regulator is used in the feedback control, the actual tuning parameters only include PI adjustment. The sum of power setting value \( P_r \) (from manual setting or AGC target load value) and PFR power increment \( \Delta P_r \) constitutes the final power setting value. The feedforward part adopts simple proportional adjustment \( K_f \), and the input value of PID feedback regulation is the deviation between the final set value and the actual power feedback value. This closed loop can ensure that there is no steady-state deviation in the final power regulation.

It can be seen from Figure 1 that the nonlinear problem of the controlled object is mainly caused by the nonlinearity of the comprehensive valve opening and the change of main steam pressure. As a result, the gain coefficient from the actual comprehensive valve opening to the steam flow entering the turbine is not fixed. In addition, due to the feedforward part, the tuning of closed-loop feedback PID parameters is generally weak, resulting in poor anti-disturbance ability of traditional control methods.

3. Multi-model generalized predictive control
In order to solve the problem that traditional control schemes cannot perform the regulation accurately, this paper adopts the generalized predictive control technology which has the most promising engineering application prospect [9, 10]. The simplified generalized predictive control has a small calculation load and a simple calculation process, and is easy to implement through the configuration of the DCS control system.

Although the generalized predictive control adopted is simplified, but for simple low-order inertial controlled objects, after reasonable tuning of the controller parameters, the control performance is not much different from traditional predictive control technology. At the same time, considering the serious nonlinearity and uncertainty of the controlled object, combined with the multi-model control strategy, an improved power regulation scheme based on multi-model generalized predictive control is proposed. The specific control structure is shown in Figure 2.
3.1. Generalized predictive control

As one of the representative algorithms of model predictive control, generalized predictive control has been successfully applied in various industrial processes [11-13]. The basic idea of this algorithm is as follows. Firstly, the future control sequence is calculated by minimizing the performance index function within the prediction horizon, and then the first step control action of the control sequence is applied to the actual controlled object, and the above process is repeated in every sampling period. The performance index function includes the deviation square value between predicted value and set value of the controlled output in the prediction horizon and the square of the control increment in the control horizon.

The specific form of the performance index function to be minimized is as follows:

\[
J = \sum_{j=N_1}^{N_2} \left[ (\hat{y}(t+j|t) - r(t+j))^2 + \sum_{j=1}^{N_2} \lambda(j) [\Delta u(t+j-1)]^2 \right] 
\]

(1)

In equation (1), \(\hat{y}(t+j|t)\) is the predicted output value of controlled quantity of step \(j\) at time \(t\), \(r(t+j)\) is the future set value sequence. \(N_1\) and \(N_2\) are the minimum and maximum values of the prediction horizon, respectively. Generally, \(N_1\) is set as the pure delay time of the controlled object, \(N_u\) is the control horizon, \(\lambda(j)\) is the sequence of control weight values, it can be set to constant value \(\lambda\). \(\Delta u(t+j-1)\) is the control increment.

The goal of predictive control is to calculate the future control sequence \(u(t), u(t+1), \ldots\) by minimizing \(J\). Thus, the predicted output of the controlled object approaches the set value \(r(t+j)\). In this algorithm, it is needed to solve the recursive expression and matrix inverse operation of Diophantine equation to obtain the output predicted value \(\hat{y}(t+j|t)\).

3.2. Algorithm simplification

For the steam turbine power regulation process, the controlled object can be approximated as a first-order plus pure delay process model, many industrial processes can be approximated as such models, and this type of model is commonly used in the PID controller tuning process. The specific structure of this model can be expressed as the following transfer function:

\[
G(s) = Ke^{\tau s} / (1 + Ts) 
\]

(2)
In equation (2), \( K \) is the steady state gain of the process, \( T \) is the process inertia time, \( \tau \) is the pure delay time of the process.

Take the sampling time as \( T_s \), equation (2) can be expressed as the following discrete form:

\[
G(z^{-1}) = \frac{bz^{-d}}{1-az^{-1}} z^{-d}
\]

(3)

The discrete parameters in the equation (3) can be expressed as:

\[
a = e^{-(T,T_s)}, \quad b = K(1-a), \quad d = \tau / T_s
\]

(4)

The controlled autoregressive integral moving average model is used to establish the random disturbance of the controlled system, the noise polynomial takes the form of step noise, and then the discrete form of the controlled object can be expressed as equation (5):

\[
(1-az^{-1})y(t) = bz^{-d}u(t-1) + e(t)/\Delta
\]

(5)

Equation (6) can be obtained by multiplying on both sides of equation (5).

\[
y(t+1) = (1+a)y(t) - ay(t-1) + b\Delta u(t-d) + e(t+1)
\]

(6)

Considering that the \( N_1 \) setting value in the performance index function (1) should be greater than the pure delay time \( d \), in order to simplify subsequent controller parameter tuning process, set \( N_1 = d+1 \), \( N_2 = d+N \), control horizon \( N_u = N \).

If \( \hat{y}(t+d+j|t) \) and \( \hat{y}(t+d+j-2|t) \) are known, from equation (6), the predicted value of \( \hat{y}(t+d+j|t) \) can be obtained as equation (7):

\[
\hat{y}(t+d+j|t) = (a+1)\hat{y}(t+d+j-1|t) - a\hat{y}(t+d+j-2|t) + b\Delta u(t+j-1|t)
\]

(7)

By recursively calculation of equation (7), \( j = 1, 2, \ldots, I \), the following prediction equation can be obtained:

\[
\hat{y}(t+d+i|t) = G_i(z^{-1})\hat{y}(t+d+i|t) + D_i(z^{-1})\Delta u(t+i-1)
\]

(8)

In equation (8), \( G_i(z^{-1}) \) is first order, \( D_i(z^{-1}) \) is i-1 order. Incorporate equation (8) into the performance index function (1), the performance index \( J \) is the function of \( y(t+d|t) \), \( \hat{y}(t+d-1|t) \), \( \Delta u(t+N_2 - d - 1) \), \( \Delta u(t+N_2 - d - 2) \), \ldots, \( \Delta u(t) \) and set value sequence function. The following expression can be obtained by minimizing the performance index function:

\[
Eu = Fy + Hr
\]

(9)

Each vector in equation (9) can be expressed as:

\[
u = \left[\Delta u(t) \Delta u(t+1) \cdots \Delta u(t+N-1)\right]^T
\]

\[
y = \left[\hat{y}(t+d+1|t) \hat{y}(t+d+2|t) \cdots \hat{y}(t+d+N|t)\right]^T
\]

\[
r = \left[r(t+d+1) r(t+d+2) \cdots r(t+d+N)\right]^T
\]

(10)

\( E \) and \( H \) are both \( N \times N \) dimensional matrix, \( F \) is a \( N \times 2 \) matrix. Let \( M \) be the first row vector of matrix \( E^{-1} \). Therefore \( \Delta u(t) \) can be calculated by the following equation:

\[
\Delta u(t) = MFy + MHr
\]

(11)

Considering that the future setting value is unknown, \( r(t+d+i) \) equals current set value, then the set value sequence can be expressed as:

\[
r = \left[1 \cdots 1\right]r(t)
\]

(12)

Thus, the equation of control increment value \( \Delta u(t) \) is obtained as follows:

\[
\Delta u(t) = p_{y_1} \hat{y}(t+d-1|t) + p_{y_2} \hat{y}(t+d-2|t) + p_{r_1} r(t)
\]

(13)

In equation (13), \( MF = [p_{y_1} \quad p_{y_2}] \), \( p_{r_1} = \sum_{i=1}^{N} M_i \sum_{j=1}^{N} r_{ij} \). Note that all coefficients \( p_{y_1}, p_{y_2}, p_{r_1} \) are function of \( a, b \) and \( \lambda \).
Then the calculation equation of position control at the current moment is as follows:

\[ u(t) = u(t-1) + \Delta u(t) \]  

(14)

Traditional predictive control methods are strict in dealing with constraints on the control action and controlled variable. Considering that the biggest advantage of predictive control method is rolling optimization, in each sampling period, the calculation will be performed again, and only the first step control action in the calculated optimal control vector is executed. Therefore, only the constraints of current control position \(u(t)\) and control increment \(\Delta u(t)\) are considered. Due to the inevitable mismatch between the internal model of the predictive controller and the actual process, only the output constraints at the next moment are considered for the output constraints of the controlled object.

The constraints of traditional predictive control can be simplified to expressions (15)- (17):

\[ u_{\text{min}} \leq u(t) \leq u_{\text{max}} \]  

(15)

\[ \Delta u_{\text{min}} \leq \Delta u(t) \leq \Delta u_{\text{max}} \]  

(16)

\[ y_{\text{min}} \leq y(t+1) \leq y_{\text{max}} \]  

(17)

Based on the above constraint expressions, the control variables expressed in equation (13) and (14) are subjected to bounder constraints to obtain the final feasible valve opening instruction.

### 3.3. Multi-model strategy

There are many ways to solve the non-linear problems of steam turbine power regulation, including non-linear control strategy, robust control strategy, and multi-model control method. The reason for choosing the multi-model control method is its less calculation amount than that of nonlinear control strategy, its easier engineering implementation, and at the same time its control performance is better than that of the robust control technology. At present, there are many cases of successful application of the multi-model control method in the industrial control process. It is a control technology that can better solve the nonlinear problem of the object and has the most promising application prospects. An improved recursive Bayesian weighting method is adopted [14], the calculated weight value can realize the combination of multiple model controllers, the control output of the multi-model controller can be obtained after weighted sum operation. The calculation equation of weight value is as follows:

\[ W_{j,k} = \begin{cases}  
    p_{j,k} & p_{j,k} > \delta \\
    \frac{p_{j,k}}{\sum_{j} p_{j,k}} & 0 < p_{j,k} \leq \delta
\end{cases} \]  

(18)

In equation (18), \(\varepsilon_{j,k}\) is the relative error value of the j-th sub-model in the multi-model method at the k-th sampling time compared to the actual output of controlled object, that is, the ratio of the absolute error value to the initial output value. \(K\) is the convergence coefficient in iterative calculation, and a large \(K\) value represents a fast convergence rate. \(p_{j,k}\) is the conditional probability of the matching degree between the output value of the j-th sub-model and the controlled object real model at the k-th sampling time.

Through the analysis of equation (16), it can be seen that at a certain sampling moment, if the matching probability of the sub-model and the real model is 0, the matching probability of the sub-model in the corresponding multi-model will always be 0, thus, the self-controller corresponding to the sub-model loses its control function, which will reduce the number of multi-model sub-controllers. In order to solve the above problems, a small positive threshold \(\delta\) can be added. When \(p_{j,k} \leq \delta\), let \(p_{j,k} = \delta\), so as to ensure that no sub-controller fails. Then the weighted value calculation of the multi-model sub-controller is modified to equation (19).

\[ W_{j,k} = \begin{cases}  
    \frac{p_{j,k}}{\sum_{j} p_{j,k}} & p_{j,k} > \delta \\
    0 & 0 < p_{j,k} \leq \delta
\end{cases} \]  

(19)
Finally, the control output values of different sub-controllers are multiplied by the corresponding weighted values and then added together, then the final actual control output of the multi-model controller obtained is expressed as equation (20).

\[ u(k) = \sum_j W_{j,k} u_j(k) \]  

(20)

4. Simulation study

In order to compare the PFR performance of the traditional power regulation system and the improved power regulation system, the controlled system is simplified to the control increment block diagram shown in Figure 3, where k is variable flow coefficient within a certain range. For the PFR of thermal power units, it is assumed that the variation range is \([0.2,0.8]\).

The simulation parameters are set as follows: The feedforward gain of traditional power regulation system is set to \(k_f = 1\); PID controller transfer function \(G_k(s) = 0.2 + 0.04/s\). The dynamic model of each link of the controlled object is set as follows: steam turbine model \(G_t(s) = \frac{1}{0.0177s^2 + 0.0333s + 1}\). For the research on improving power regulation, four sub-generalized predictive controllers are designed, and the internal model flow coefficients are set to 0.2, 0.4, 0.6 and 0.8. The calculation period of each sub-controller is set to 0.5s, and other controller parameters are set as \(N_1=1, N_2=30, N_u=1, \lambda=0.001\).

Let the flow coefficient k be 0.3, 0.5 and 0.7, respectively. A PFR simulation test is carried out on both the traditional power regulation system and the improved power regulation system. The comparative response curves are shown in Figure 4, Figure 5 and Figure 6. It can be seen from the figures that the improved method is significantly better than the traditional power regulation method under the three conditions. The PFR load tracking capability shows better robustness during the change of flow coefficient, with faster adjustment and better adaptive ability. While, the PFR performance of the traditional power control system shows a large performance difference during the change of the flow coefficient, robustness is poor, and certain extent oscillation occurred in the regulation process resulting in poor stability.

The PFR performance indexes of the two methods in Figure 4, Figure 5 and Figure 6 are listed in Table 1. It can be seen from the table that as the flow coefficient increases, the PFR performance indicators of both methods show certain improvement. However, the change of k value has a greater impact on the PFR performance of traditional method. When the value of k is small, the traditional method has the problem of insufficient output of PFR ability. According to the requirements of power grid dispatching index, the requirements for the PFR response index are as follows: From 0 to 15 seconds, from 0 to 30 seconds, and from 0 to 45 seconds, the PFR response index must reach 0.4, 0.6, and 0.7, respectively. It can be seen that the traditional power regulation method fails to meet the assessment standard when the flow coefficient is small. In contrast, the improved power regulation method always maintains a better power response characteristic under the condition of a wide range variation of flow coefficient, which ensures the safe and stable operation of the units.
Figure 4. Control performance comparison curve when the flow coefficient is 0.3.

Figure 5. Control performance comparison curve when the flow coefficient is 0.5.

Figure 6. Control performance comparison curve when the flow coefficient is 0.7.

Table 1. The comparison of PFR performance indexes of before and after improvement.

| Flow coefficient | Traditional method | Improved method |
|------------------|--------------------|-----------------|
|                  | 15s  | 30s  | 45s  | 15s  | 30s  | 45s  |
| 0.3              | 39.5%| 51.4%| 59.9%| 72.6%| 89.4%| 95.9%|
| 0.5              | 60.3%| 73.9%| 81.5%| 85.8%| 96.4%| 99.1%|
| 0.7              | 77.7%| 89.9%| 94.6%| 91.5%| 98.4%| 99.7%|

5. Conclusions
In order to solve the nonlinear problem of the controlled object in the power regulation of the steam turbine generator set, an improved power regulation system is designed based on the multi-model predictive control method. The improved scheme solves the problem of non-linear flow coefficient
caused by valve flow characteristics and pressure influence by combining the improved multi-model adaptive strategy. Sub-controllers are designed based on simplified generalized predictive control strategy, and the complexity of predictive control design is reduced. Through the PFR simulation and the statistical comparison of PFR performance indicators with traditional power regulation method, it is proved that the improved scheme is superior to the traditional power regulation method in terms of set-point tracking and system robustness.

In addition, the improved power regulation algorithm needs less calculation, the calculation structure is simple and this algorithm is easy to implement through DCS platform, therefore it has greater engineering application value.

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