Dynamic Matrix Based Thermal Power Tracking Control of Nuclear Power Reactor

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Abstract: power control of nuclear power plant is an important technology to ensure the safe and efficient operation of nuclear power unit. Because the power system of nuclear power reactor belongs to nonlinear system, there are many factors affecting the distribution of thermal power, which leads to the uncertainty of the tracking target of thermal power of nuclear power reactor. Therefore, this paper proposes a dynamic matrix-based thermal power tracking control method for nuclear power reactors. The dynamic matrix algorithm is used to establish the prediction model of the controlled object, to determine the tracking target value, to design the dynamic matrix controller, and to formulate the switching strategy combined with the minimum value of the cumulative prediction error, and to realize the thermal power tracking control of the power reactor. Simulation results show that the proposed method has different target values under different working conditions in accordance with the actual control value, it has better engineering value and practical significance for reducing the working intensity of operators and improving the performance of load tracking.

1. INTRODUCTION

In the process of peak-shaving, the power reactor power of nuclear power unit plays a key role in the overall operation of nuclear power plant, and plays a decisive role in the smooth and efficient operation of nuclear power unit. The power control system is complex, and its parameters are the correlation function of running power, fuel combustion degree and the value of the control rod. Therefore, under the tracking load instruction, it is necessary to track and control the power of power reactor effectively.

In view of the above problems, researchers in related fields have made some achievements. The power control method of power reactor based on BP neural network is proposed [¹] in the literature. This study uses the power distribution of the core to reflect a large amount of information. However, in practical application, the target value obtained by this study is quite different from the actual control value, which indicates that the application performance is not ideal. Document [²] use online fuzzy prediction model to control power of power reactor. However, the global control effect of this method is not good, and there will be errors between reference input and actual output.

For solving the problems of traditional methods, dynamic matrix method is used [³] track and control the thermal power of nuclear power plant. The dynamic model of the system is constructed by using the step response characteristics of the controlled target. The modelling method is simple and the calculation is small. Through the model error feedback correction, the uncertainty in the traditional method is improved, and the accuracy and robustness of the system control are improved.
2. Dynamic Matrix-based Dynamic Reactor Thermal Power Tracking Control

2.1 Main Influencing Factors of Thermal Power Distribution

The power of nuclear power reactor is constantly changing during operation. The change is affected by many factors, including moderator temperature, flammable poison effect and so on.

2.1.1 Effect of moderator temperature

The effect of moderator temperature on power distribution is mainly reflected in the increase of core temperature from bottom to top. During stable operation, the moderator temperature transformation will reduce the overall power of the core, resulting in negative value ∆I axial power error.

After adjusting the concentration of boron, the reaction degree of core was controlled. According to the change of boron influencing factors, the differential value of boron is always negative, when the concentration is fixed, the negative reactivity decreases with the increase of moderator temperature, and the negative reactivity decreases with the increase of boron concentration.

2.1.2 Effect of Doppler effect

As the power of the power reactor increases, the fuel temperature increases, which is the negative temperature effect caused by the Doppler effect, that is, the change of the fuel temperature coefficient.

In general, the Doppler temperature effect belongs to the transient transformation quantity. Under the influence of fuel energy consumption and temperature, the fuel consumption increases, the Doppler temperature effect increases, and occupies the main position in the whole core life period.

2.1.3 Effects of flammable poisons

Combustible poison is one of the influencing factors of storage reactivity of power reactor. The reactivity of combustible poison must be the same as the residual reactivity of nuclear fuel consumption in the core. Because the combustible poison rod exists on the whole core, it will not have too much effect on the power distribution in the initial stage, but over time, the burning consumption of combustible poison at the bottom of the core at the end of life increases and the neutron absorption performance decreases, thus affecting the ∆I.

2.1.4 Effect of xenon toxicity

Xenon Xe-135 is an important isotope in fission products of power reactor. It is formed by the decay I-135 fission and decay through the decay chain of fission products and disappears by the way of neutron absorption. For xenon, the thermal neutron absorption cross section is large, which will have an important effect on the neutron flux distribution and ∆I of the power reactor.

The formation and disappearance of xenon in the power reactor have the following characteristics: when the power reactor starts, the equilibrium state of xenon concentration will appear after stable operation, this stage time is about 40h; the negative reactivity of equilibrium xenon poison in stable operation is only related to power, the higher the power is, the greater the xenon poison is; when stopping, xenon poison is affected by point pit factor, it will go through a long poison-maximum-disinfection process, the maximum xenon poison time is about 11 h, and the depth of point pit is related to power of power reactor, the higher the power pit is deeper; the xenon poison is disappeared by adsorption of neutron by using the method of decreasing power gradually; Neutron flux density during power rise. The change of xenon poison was first reduced and then increased to equilibrium.

According to the analysis of the main influencing factors of the thermal power distribution above, the four influencing factors are eliminated in the following research process, so as not to affect the accuracy of the research results.
2.2 Characteristic analysis of thermal power of power reactors

Based on the influence analysis of 2.1 thermal power distribution, the mathematical model of power reactor power of fuel, coolant temperature and single set of equivalent retarded neutrons is [7] as follows:

\[
\dot{n}_r = \frac{P_0 - \beta}{A} n_r + \frac{\beta}{A} c_r + \frac{n_r}{A} \left[ \alpha_f (T_f - T_{f,m}) + \alpha (T_{cav} - T_{cav,m}) \right]
\]

\[
\dot{c}_r = \lambda n_r - \dot{c}_r
\]

\[
\dot{T}_f = -\frac{\Omega}{\mu_f} T_f + \frac{\Omega}{\mu_f} T_{cav} + \frac{P_0}{\mu_f} n_r
\]

\[
\dot{T}_{cav} = -\frac{2M + \Omega}{\mu} T_{cav} + \frac{\Omega}{\mu} T_f + 2M T_{cav}
\]

\[
\rho_c = G z_r
\]

In the formula, \( n_r \) represents relative power, \( \beta \) represents the share of a single set of slow-onset neutron \( \lambda \), \( c_r \) the first drive nuclear density, \( \Lambda \) represents neutron lifetime is decay constant, \( \alpha_f \) is the fuel reactivity temperature coefficient, \( P_0 \) represents rated thermal power, \( G_r \) represents the differential value of the control rod, \( \rho_r \) indicates the degree of response to the rod movement, \( T_{f,m} \) mean fuel temperature, \( T_{cav,m} \) mean coolant temperature, \( \Omega \) is the heat transfer coefficient between fuel and coolant, \( \mu_f \) represents the total thermal capacity of the fuel.

During the operation of the power reactor, the energy generated by the fission of nuclear fuel is discharged by the coolant. In the power reactor power control system, the control speed belongs to the control quantity, and the relative power and the average coolant temperature are the output quantity. In order to ensure the efficient and stable operation of the power reactor of nuclear power plant, the following constraints must be set on the control quantity and output quantity:

\[
\begin{align*}
max z_r \leq z_{r,max} \\
min z_r \leq z_{r,min} \\
n_{r,min} \leq n_r \leq n_{r,max}
\end{align*}
\]

In formula, \( n_{r,max}, n_{r,min}, z_{r,max} \) and \( z_{r,min} \) represent the upper and lower limits of the relative power and the rate of the control rod, respectively; the \( \Xi \) represents the \( n_R \) discrete values selected.

Controller’s main task is to collect the speed signal [8] of the control rod, adjust the power tracking load and minimize the moving distance of the control rod. When the system reference points are set to \( n_{r,d}, c_{r,d}, T_{f,d}, T_{cav,d} \) and \( \rho_{c,d} \), use the following formula to calculate the actual values of these reference points:

\[
\begin{align*}
\rho_{c,d} + \alpha_f (T_{f,d} - T_{f,m}) + \alpha (T_{cav,d} - T_{cav,m}) &= 0 \\
n_{r,d} &= c_{r,d} \\
-T_{f,d} \Omega / \mu_f + T_{cav,d} \Omega / \mu_f + n_{r,d} P_0 / \mu_f &= 0 \\
-T_{f,d} \Omega / \mu_f - T_{cav,d} (2M + \Omega) / \mu_c + 2T_{cav} M / \mu_c &= 0 \\
z_{r,d} &= 0
\end{align*}
\]

Choose \( u = z_r \) is state vectors:

\[
x(k+1) = f(x(k), u(k)) = x(k) + \int_{t_k}^{t_{k+1}} f(x(\tau), u(k)) d\tau
\]

In formula (4), the \( k \) represents the sampling time and the \( T_S \) represents the sampling time.

The nonlinear system of power reactor of nuclear power plant belongs to the classical two-time scale system, which mainly shows as follows:
(1) At the time of fission, most of the transient neutrons appear immediately, and a small number of transient neutrons are released after the decay of a variety of intermediate fission products.

(2) The heat generated by the crack in the power reactor is transmitted to the coolant through heat conduction and heat convection, and the average reaction time constant between the fuel and the coolant is higher than that of the transient neutron occurrence period. The eigenvalues of the linear model of the thermal power of the power reactor are shown in the following table:

| $n_i$ | 0.2 | 0.4 | 0.6 | 0.8 | 1 |
|-------|-----|-----|-----|-----|---|
| $S_{\text{max}}$ | -65.61 | -66.6 | -65.43 | -65.34 | -66.54 |
| $S_{\text{min}}$ | -0.02 | -0.27 | -0.33 | -0.37 | -0.04 |
| $S_{\text{max}} / S_{\text{min}}$ | 3213 | 2465 | 2014 | 1598 | 1653 |

Table 1 shows that the motion modes of local linear models with different eigenvalues are different, the maximum eigenvalue $S_{\text{max}}$ corresponds to the neutron generation process, and the minimum eigenvalue $S_{\text{min}}$ corresponds to the heat transfer process. These two processes are the basic reasons for the existence of double time scale in power reactor thermal power system.

2.3 Power tracing control for power reactors

The dynamic matrix method is a predictive control method based on the step response of the controlled object $a_i = a(iT)$, $i=1,2,...,T$ is the sampling period. For the goal of gradual stabilization, a step response will gradually appear stationary at any time, therefore $a_N$ the steady-state value of step response of the system at $t \rightarrow \infty$ is $a_\infty$. Therefore, $\{a_1, a_2, ..., a_N\}$ used in the prediction model of the controlled target M continuous control $\Delta u(k), ..., \Delta u(k+M-1)$ representation:

$$\tilde{y}_M(k+i|k) = \tilde{y}_0(k+i|k) + \sum_{j=1}^{\min(M,i)} a_{i-j+1} \Delta u(k+j-1), i = 1, ..., N$$

In the formula, the prediction model $\tilde{y}_M$ represents the M time point and $\tilde{y}_0$ represents the original estimate.

On the basis of the above prediction model, the performance optimization index is as follows:

$$\min J(k) = \sum_{i=1}^{M} \sum_{j=1}^{M} \omega(k+j-1) - \sum_{i=1}^{M} a(k+i) - \sum_{i=1}^{M} \sum_{j=1}^{M} a(k+j-1) - \tilde{y}_M(k+i|k)$$

Formula, $\omega(k+1)$ represents the system tracking target value.

For the acquisition of control quantities that enable $J(k)$ to reach a minimum $\Delta u_M(k) = [\Delta u(k), ..., \Delta u(k+M-1)]^T$, according to the necessary conditions of extreme value, it can be concluded that:

$$\Delta u_M(k) = \left(A^TQA + R\right)^{-1} A^TQ \left[w_p(k) - \hat{y}_{p0}(k)\right]$$

(7)

The optimal value of $\Delta u(k)$, ..., $\Delta u(k+M-1)$ is reflected in formula (7) at the time point. When the first control quantity $u(k)$ is only applied to the target in the dynamic matrix method, the control $u(k+1)$ is obtained by using the $k+1$ instead of $k$ the same calculation process at the next time point.

$$\hat{y}_{\text{cor}}(k+1) = \tilde{y}_M(k+i|k) + he(k+1)$$

(8)

In formula (8), $e(k+1)$ represents the difference between the estimated value and the true value of the system at the $k+1$ time point, $h$ belongs to the correction coefficient.

When the time base point reaches the $k+1$ time, the revised estimate $\hat{y}_{\text{cor}}(k+1)$ must use the left multiplication $U$ matrix to realize the displacement, and the obtained result is regarded as the initial prediction value at the next moment:
\[
\tilde{Y}_{No}(k+1) = U\tilde{Y}_{cor}(k+1)
\]  
\text{(9)}

Formula, 
\[U = \begin{bmatrix}
0 & 1 & 0 \\
\vdots & \ddots & \vdots \\
0 & \cdots & 0 & 1
\end{bmatrix}
\]

On the basis of the above dynamic matrix algorithm, the tracking controller is designed considering the non-stability characteristics of the dynamic reactor thermal power adjustment.

For this non-stable target with integral link, the step response moves in a straight line at a fixed speed after a period of time. At this point, it can be considered that after the \(t_N = NT\) of a certain time point. On the basis of this characteristic, the displacement matrix of the self-stable system in formula (9) is transformed into \(S_{nus}\), to eliminate the saturation state \([10]\) of the tracking controller, in which:

\[
\begin{pmatrix}
0 & 1 & 0 \\
\vdots & \ddots & \\
0 & \cdots & 0 & 1
\end{pmatrix}
\]

As long as the step response of the controlled target around the balanced working point is obtained and the optimal correction coefficient is determined \(h_1, h_2, ..., h_3\) the local tracking controller with good control effect can be designed by using the dynamic matrix method.

For the local controller, if the power control is carried out in the global range, the control effect will deteriorate. The main reason is that the step response coefficient in the local matrix controller is produced by the step response near the working point. At this time, the prediction model will appear mismatch because of the improper step response coefficient.

Therefore, the controller of the global system is:

\[
\rho(t) = \sum_{i=1}^{M} \varphi_i(n_r)\rho'(t)
\]  
\text{(11)}

Formula, \(\varphi_i(n_r) = \frac{M_i(n_c)}{\sum_{j=1}^{M} M_j(n_c)}\)

Fig.1 Structure diagram of power controller for power reactor

Combined with the schematic diagram of power reactor thermal power controller, the switching strategy is formulated. Suppose that the total prediction error \(l\) by any prediction model at \(k\) time point in a limited time period is expressed as:
\[ J_i(k) = \chi e_i(k) + \gamma \sum_{j=i}^{S+1} \exp(-j\lambda) e_j(k-j), (i = 1, 2, ..., S+1) \]

Formula, \( e_l(k) = \frac{y(k)-y_k}{\sqrt{(c+\phi(t-1))^T \phi(t-1)}} \)

Represents the actual output error of the model and the system, \( c > 0 \), the \( l \) represents the cumulative length, the \( \chi \) and \( \gamma \) are the adjustment constants, the \( \lambda \) s belongs to the forgetting factor, and the \( S \) represents the number of fixed models.

Dynamic matrix based thermal power tracking controller of nuclear power plant is realized by switching between \( S+1 \) sub-controller. The minimum value of the cumulative prediction error \( j_i(k) = (i = 1, 2, ..., S+1) \) is combined to switch the corresponding controller to realize local and global control.

3. Simulation experiment and analysis

In order to verify the dynamic matrix tracking control performance of nuclear power plant power reactor, the following simulation experiments are carried out. The other parameters in the simulation experiment are as follows: modelling time domain \( N=20 \), prediction time domain \( P=20 \), effective control time domain \( L=6 \), total deviation length \( l=30 \).

To better prove the tracking control effect of the proposed method, this experiment takes the literature \([1]\), the literature \([2]\) method as the control method, and obtains the dynamic reactor thermal power tracking control results of several different methods under the following different working conditions.

(1) Local control conditions: the experimental time is 800s, the initial operation of the controller is 100% rated power stable condition, the experimental results are as follows:

![Figure 2 Power tracking results of different methods under local control conditions](image)

(2) Global control conditions: the experimental time is 4000s, the controller changes to 12% rated power at a speed of 5% per minute at 700s and 100% rated power at 2500s. The experimental results are as follows:
From Fig 2~ Fig 4, it can be seen that the proposed control method achieves ideal results under three different working conditions. In local and global working conditions, the power reactor power of this method appears slight overshoot and weak vibration phenomenon, while the other two methods do not vibrate obviously under local working conditions, but overshoot is higher under global working conditions. And cannot achieve stability in a short period of time. In addition, under emergency conditions, the control effect of dynamic matrix controller on overshoot and regulation time is still...
ideal, which meets the requirements of safe operation of nuclear power plant, but the actual control value of the other two methods is far from the target value. Not suitable for emergency conditions. Because the control switching strategy designed in this paper is reasonable and can satisfy the power tracking control of power reactor under any working condition.

4. Conclusion
In order to ensure the efficient and stable operation of nuclear power unit, this paper puts forward the dynamic matrix based thermal power tracking control of nuclear power plant power reactor. In the model acquisition and control algorithm, the existing dynamic performance of multi-module nuclear power plant is comprehensively analysed, and better power tracking control performance is reflected under the premise of ensuring the safety of power reactor. However, there is still a real-time problem, so this method is limited to some slow industrial processes. How to use dynamic management and other technologies to improve real-time will become the focus of future research.

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