International Journal of Control and Automation
Vol. 8, No. 1 (2015), pp. 305-316
http://dx.doi.org/10.14257/ijca.2015.8.1.28

Performance Assessment of Power Plant Main Steam Temperature Control System based on ADRC Control

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Abstract

This paper makes an assessment of the typical main steam temperature system in thermal power plant. Due to main steam temperature system is a cascade control system. So, it should be assessed with the performance assessment method of cascade control systems. So firstly, this paper deduces the theoretical process of performance assessment of cascade control system based on minimum variance. Then with this method assesses the performance of four typical loads in thermal power plants when using active disturbance rejection-proportion (ADRC-P) cascade control and smith active disturbance rejection-proportion (SADRC-P) cascade control respectively. Finally, makes comparison of the results. Results show that, when using the same control strategy, different loads has different performance. Load with lager inertia has better performance; When using different control strategies, performance under SADRC-P control is better than that under ADRC-P control.

Keywords: *Performance assessment, Main steam temperature control system, ADRC-P control system, Smith ADRC-P control system*

1. Introduction

In the early operation of the control system, the controller always exhibits good control performance [1]. However, after operating for a long time, the performance of the controller will deteriorate owing to friction and wear of the actuators, change of process characteristics, lack of maintenance, disturbance and other factors. With the method of performance assessment, we can directly reflect the status of the system as well as the existing problems to the control engineers. Then the engineers can adjust the operations timely thus avoiding unnecessary production loss. This is important for the long-term stable operation of the system. The key of performance assessment is to find a benchmark. Minimum variance benchmark put forward by Harris in 1989 is the most widely used [2]. In the benchmark, we use the ratio of ideal variance and actual variance to assess whether the control system is performing well or not. Here the ideal variance is the variance under minimum variance controller. Minimum variance index or Harris index is used to assess the random performance of the system, performance of disturbance rejection when steady-state system subject to random disturbance.

In modern thermal power plant process control system, boiler superheated steam outlet temperature (main steam temperature) is one of the main parameters of the boiler, and has an important influence on the safe operation of the plant [3]. When the main steam temperature is too high, the superheater and steam turbine will be damaged due to enduring excessive thermal stress, thus threatening the safe operation of the unit; When the main steam temperature is too low, it will lower the thermal efficiency of the unit, thus having an impact on the economy of the units. So it is important to control the main steam system. Considering the main steam temperature target has the characteristics of large inertia, large delay and time-varying, many scholars apply ADRC control strategy

ISSN: 2005-4297 IJCA

and Smith ADRC control strategy to main steam temperature control system. And it turns out that using these control strategies can effectively improve the dynamic response of control system.

This paper taking a 600MW supercritical once-through boiler for study assesses the performance (rejection of random disturbance) of four typical loads under ADRC control and Smith ADRC control respectively.

2. Main Steam Temperature Control System

Since the length of the superheater pipe and the volume of the steam are large [4]. So when the water which makes the temperature of the steam down changes, the outlet temperature of the superheater will have a large delay. Besides, when the load changes, there will be an obvious change of the dynamic characteristics of the main steam temperature. Therefore, the main steam temperature system not only has the characteristics of large delay, large inertia and time-varying, but also has the characteristics of parameter distribution susceptible to interference, which increases the difficulty of controlling the system. At present, most power plants use cascade control structure shown as Figure 1 to control the main steam temperature. The secondary loop uses P or PI controller to eliminate bias of the leader region's steam temperature, adjusting the main steam temperature coarsely. The main loop uses PID controller to overcome the large delay and large inertia of the inertia area. For the secondary loop, it is easy to tune the parameters to the best, but not for the main loop. It is always the case, the same PID parameters perform well in one load, but not in another load.

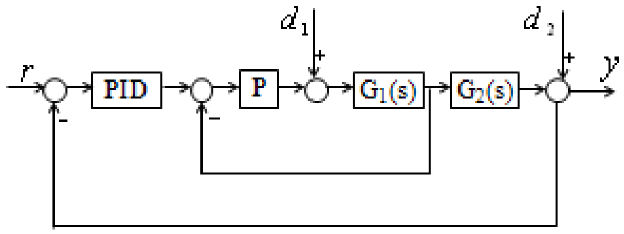

Figure 1. Cascade Control System Diagram

So many scholars put forward other control strategies. On one hand, active disturbance rejection control (ADRC) has an ability to resist external disturbance and object uncertainty [5]. So some scholars apply it to the main steam control system. Main loop uses ADRC controller and secondary loop uses P control, shown as Figure 2. And this strategy has achieved good results.

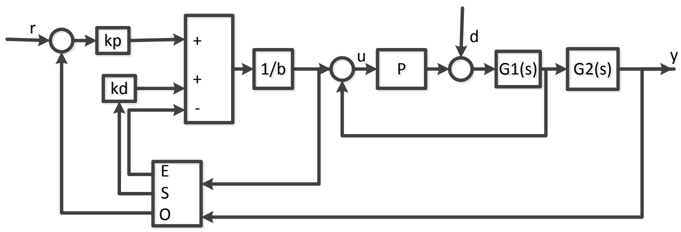

Figure 2. ADRC Cascade System Block Diagram

On the other hand, for pure lag and large delay systems, Smith put forward a completely estimated compensation strategy in 1957. It works like this: simplify the dynamics of the controlled object under basic disturbance to a mathematical model of a pure delay with a first-order inertia in series. According to the mathematical model, predictor pre-estimate the possible effect on the controlled object of the applied control action, without waiting for the controlled object reacting. This process will obviously improve the dynamic performance of the control system. In order to make full use of the advantage of smith structure, some scholars presented Smith ADRC control strategy [6], combining ADRC control with Smith control shown as Figure 3. This strategy has achieved good results too when applied to main steam temperature control system.

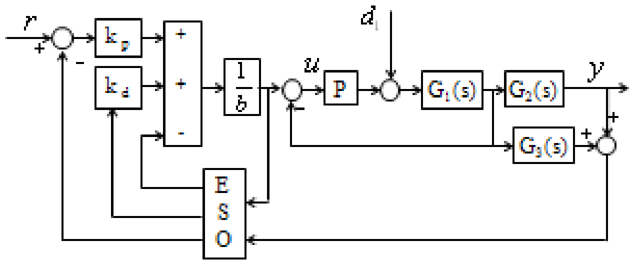

Figure 3. Smith ADRC Cascade System Block Diagram

It has proven by a lot of scholars that Smith ADRC control and ADRC control can effectively improve the dynamic performance of the system. How about the performance of other aspects of these strategies? This article just from the point of disturbance rejection assesses the performance of the systems shown as Figure 2 and Figure 3.

3. Performance Assessment of Cascade Control System

For the control strategies put forward above all use cascade control structure. So if we want to assess the systems above, we should use the method of performance assessment based on cascade control. In the following chapter we will simply deduce the theoretical process of performance assessment of cascade control system based on minimum variance. For more details, you can refer to [7].

Performance assessment based on minimum variance is the process of extracting the feedback invariants using input and output data. For cascade control system, the principle of minimum variance control is to obtain the minimum variance of the main controlled variable when the random disturbance is added into the main loop and secondary loop [8].

Figure 4 is a discrete cascade control system when random disturbance simultaneously acts on the main loop and the secondary loop. Subscript 1 in this figure refers to the primary control loop, while subscript 2 refers to the secondary control loop. $c_1(k)$ and $c_2(k)$ are the process outputs of primary loop and the secondary loop, respectively. $c_1(k)$ is the deviation variable from its set point and $c_2(k)$ is the deviation of the secondary output from its steady-state value, which is required to keep the primary output at its set point. $G_1(q) = G_1^*(q)q^{-\tau_1}$ is the process transfer function in the primary loop with time delay equal to τ_1, and $G_1^*(q)$ is the primary process model without any time delay. The disturbance filters $G_{L11}(q)$ and $G_{L12}(q)$ are assumed to be rational functions of q^{-1}, and they are driven by zero-mean white noise sequences $\varepsilon_1(k)$ and $\varepsilon_2(k)$, respectively. Similarly, for the secondary loop, we have $G_2(q) = G_2^*(q)q^{-\tau_2}$ as the process transfer function in the secondary loop with time delay equal to τ_2, and $G_2^*(q)$ is the secondary process model without any time delay. The combined effect of all unmeasured disturbances to the secondary output is represented as a superposition of disturbance filters

$G_{L21}(q)$ and $G_{L22}(q)$ driven by zero-mean white noise sequences $\varepsilon_1(k)$ and $\varepsilon_2(k)$, respectively.

Using block-diagram algebra, it can be seen simply from Figure 4.

$$C_1(k) = G_1(q)C_2(k) + G_{L11}(q)\varepsilon_1(k) + G_{L12}\varepsilon_2(k)$$
$$C_2(k) = G_2(q)u_2(k) + G_{L21}(q)\varepsilon_1(k) + G_{L22}\varepsilon_2(k) \quad (1)$$

Where $u_2(k)$ is the manipulated variable in the secondary control loop. The minimum variance control (MVC) algorithm for the system is given by

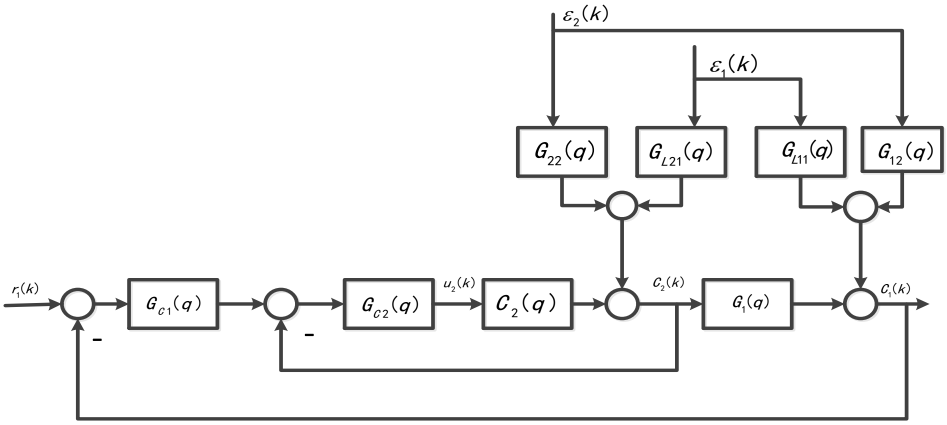

Figure 4. Cascade Control System Block Diagram

Primary Controller

$$G_{c1,MV} = \frac{G_1^*(Q_{22}R_{21} - Q_{21}R_{22}) + (R_{11} + T_1)G_{L22} - (R_{12} + T_2)G_{L21}}{(Q_{11} + S_1q^{-\tau_1})(R_{12} + T_2 + G_1^*R_{22}) - (Q_{12} + S_2q^{-\tau_1})(R_{11} + T_1 + G_1^*R_{21})} \quad (2)$$

Secondary Controller

$$G_{c2,MV} = \frac{(Q_{11} + S_1q^{-\tau_1})(R_{12} + T_2 + G_1^*R_{22}) - (Q_{12} + S_2q^{-\tau_1})(R_{11} + T_1 + G_1^*R_{21})}{G_1^*[G_{L11}S_2 - G_{L12}S_1 + (R_{11}Q_{12} - R_{12}Q_{11})q^{-\tau_2}]} \quad (3)$$

where $Q_{11}(q)$ and $Q_{12}(q)$ are polynomials in q^{-1} of order $\tau_1 + \tau_2 - 1$, and $Q_{21}(q)$, $Q_{22}(q)$, $S_1(q)$ and $S_2(q)$ are polynomials in q^{-1} of order $\tau_2 - 1$ and $R_{ij}(q)(i, j = 1,2)$ are proper transfer functions that satisfy the following Diophantine identities [9].

$$G_{L11} = Q_{11} + R_{11}q^{-\tau_1-\tau_2}$$
$$G_{L12} = Q_{12} + R_{12}q^{-\tau_1-\tau_2}$$
$$G_{L21} = Q_{21} + R_{21}q^{-\tau_2}$$
$$G_{L22} = Q_{22} + R_{22}q^{-\tau_2} \quad (4)$$

(4)

$$G_1^*Q_{21} = S_1 + T_1q^{-\tau_2}$$

$$G_1^* Q_{22} = S_2 + T_2 q^{-\tau_2}$$

The primary output $C_1(k)$ under this optimal control algorithm is MA process of order $\tau_1 + \tau_2 - 1$, that is:

$$C_1(k) = [Q_{11}(q) + S_1(q) q^{-\tau_1}]\varepsilon_1(k) + [Q_{12}(q) + S_2(q) q^{-\tau_1}]\varepsilon_2(k) \quad (5)$$

The minimum variance of $C_1(k)$ is:

$$\sigma^2_{C_1,MV} = trace\ \{(\sum_{i=0}^{\tau_1+\tau_2-1} N_i^T N_i)\sum\nolimits_{\varepsilon}\} \quad (6)$$

Where $N_i (i = 0,1,......, \ \tau_1 + \tau_2 - 1)$ are defined as the coefficient matrices of the matrix polynomial $[(Q_{11} + S_1 q^{-\tau_1})(Q_{12} + S_2 q^{-\tau_1})]$, and $\sum_{\varepsilon}$ is the variance-covariance matrix of the white noise vector $[\varepsilon_1(k)\varepsilon_2(k)]^T$.

In summary, the basic of performance assessment of cascade control system is to obtain the closed loop transfer functions. One is from main disturbance to output and the other is from secondary disturbance to output. Then use the impulse-response coefficients of the transfer functions and the estimated variance-covariance matrix to estimate the minimum variance. The closed-loop transfer functions can be obtained from the first row of the transfer function matrix estimated via multivariate time-series analysis of $[C_1(k), C_2(k)]^T$. For this analysis, an AR model [arx] setting an empty input can be used efficiently with its computational speed. Alternatively, a state space model can be estimated via the prediction error method [PEM] or a subspace identification method [n4sid]; The sample variance-covariance matrix of the residual vectors thus provides an estimate of the variance and the covariance elements of the innovation sequences. The closed-loop impulse-response coefficients can then be determined via simple correlation analysis between the output variables and the estimated innovations sequences, or by long division method.

The minimum variance estimated from the cascade control system is as follows:

$$\begin{aligned}\sigma^2_{C_1,MV} &= \mathrm{var}\{(h_{10} + h_{11}q^{-1} + ... + h_{1,\tau_1+\tau_2-1} q^{-(\tau_1+\tau_2-1)})\varepsilon_1 \\ &\quad + (h_{20} + h_{21}q^{-1} + ... + h_{2,\tau_1+\tau_2-1} q^{-(\tau_1+\tau_2-1)})\varepsilon_2\} \\ &= trace\{(\sum_{i=0}^{\tau_1+\tau_2-1} \hat{N}_i^T \hat{N}_i)\hat{\sum}_{\varepsilon}\}\end{aligned} \quad (7)$$

The performance index of cascade control system is:

$$\eta = \frac{\sigma^2_{C_1,MV}}{\sigma^2_{C_1}} \quad (8)$$

Where $\sigma^2_{C_1,mv}$ is the minimum variance, $\sigma^2_{C_1}$ is the actual variance of the system.

4. Simulation Results

The article assesses four typical loads of a 600MW supercritical boiler under Smith ADRC control and ADRC control, respectively. The process of assessment is as follows: First, set reference value of the system to 0, then add white noise with mean 0, variance 1 and 0.01 to the main loop and the secondary loop respectively. Using the simulink in MTALAB build a model, then obtain the output data of the process. Using the data perform a multivariate time series analysis to obtain the transfer functions from disturbance to the main output. After this, calculate the impulse response coefficients of the transfer functions. And finally calculate the performance index with the coefficients. The models built by simulink are shown as figure 5 and figure 6. Figure 5 is 37% load under Smith ADRC-P cascade control system and figure 6 is 37% load under ADRC-P cascade control system. Similarly, we can build the models of other loads.

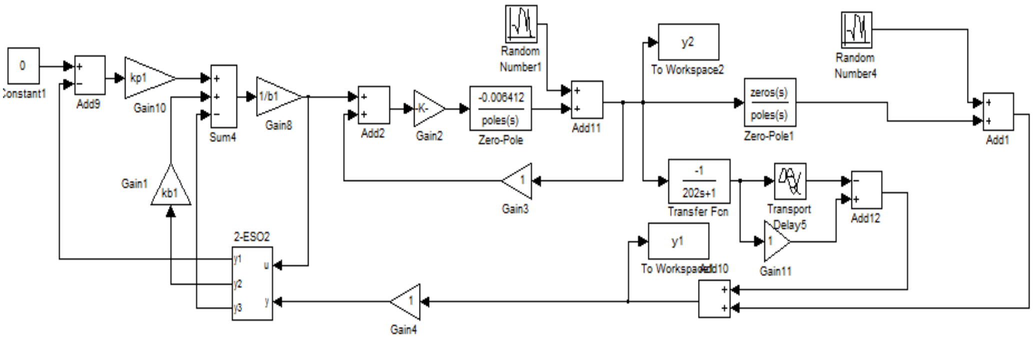

Figure 5. 37% Load Under Smith ADRC - Proportional Cascade Control System

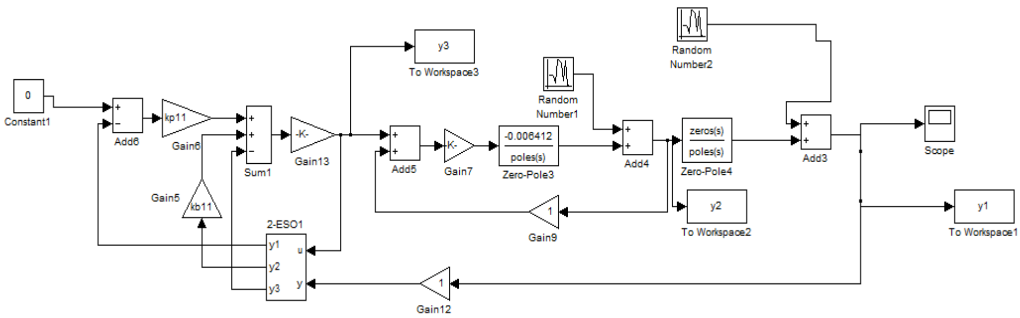

Figure 6. 37% Load under ADRC - Proportion of Cascade Control System

The parameters of the models are shown as Table 1 and Table 2. Table 1 are the dynamic characteristics of four typical loads when the main steam subject to spray disturbance. D is the main steam flow. Table 2 are the smith models of controlled object

Table 1. Transfer Functions of Four Typical Loads in Main Steam Temperature due to Spray-Water Disturbance

Load (kg/s)	Temperature of leading area /(℃/(kg/s))	Temperature of inert area /(℃/℃)
load 1 37%(D=179.2kg/s)	$-5.027/(1+28s)^2$	$1.048/(1+56.6s)^8$
load 2 50%(D=242.2kg/s)	$-3.076/(1+25s)^2$	$1.119/(1+42.1s)^7$
load 3 75%(D=347.9kg/s)	$-1.657/(1+20s)^2$	$1.202/(1+27.1s)^7$
load 4100%(D=527.8kg/s)	$-0.815/(1+18s)^2$	$1.276/(1+18.4s)^6$

Table 2. Smith Models of Controlled Object

Load	$G_2(s)/(℃/(kg/s))$	τ
load 1 37%(D=179.2kg/s)	-1/(1+202s)	302
load 2 50%(D=242.2kg/s)	-1.071/(1+117s)	194.5
load 3 75%(D=347.9kg/s)	-1.151/(1+72s)	150.6
load 4 100%(D=527.8kg/s)	-1.215/(1+36s)	85.5

4.1. Performance Assessment of Different Loads

Use the parameters tuning method in literature [10] to tune the ADRC controller parameters. In this method, it unity the parameters in the extended state observer to wo and unity the parameters in the feedback control law to wc. wo is the bandwidth of the observer, wc is the bandwidth of the controller. So the parameters which need to be tuned in the controller are only wc and wo.

First, we assess the performance of different loads under ADRC control and S-ADRC control respectively to see how the loads affect the performance of the system.

In the process of assessment, we only change one parameter. The other parameters are tuned to the optimal and kept unchanged. We gradually change parameter wo. The results obtained are shown as the following bar graphs.

Figure 7 and figure 8 are the results when the system is under smith ADRC control. Figure 7 is the variance of different loads and Figure 8 is the performance index of different loads.

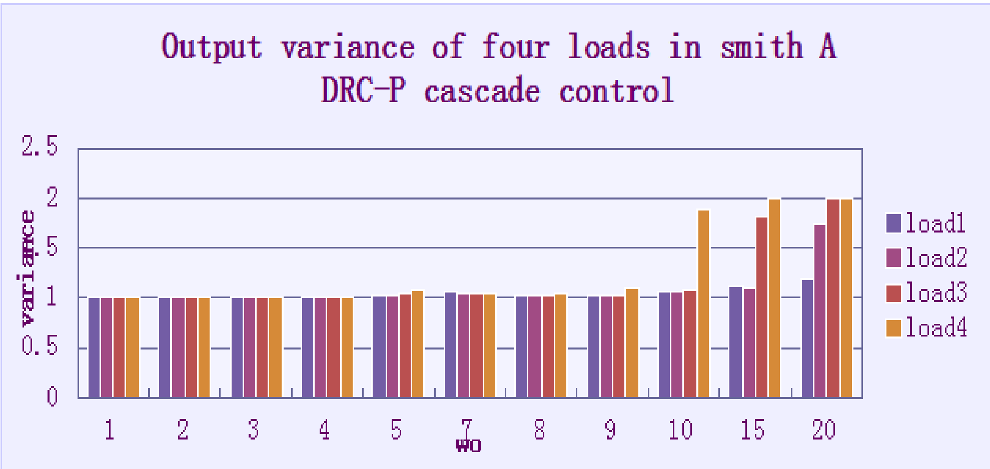

Figure 7. Output Variance of Four Typical Loads in Smith ADRC-P Cascade Control

In the above figure, when wo are equal to 15 and 20, variance in load 3 and load 4 are equal to 2, but that are not the true case, the true variances are very large. In order to make an obvious contrast, we set the variance to 2.

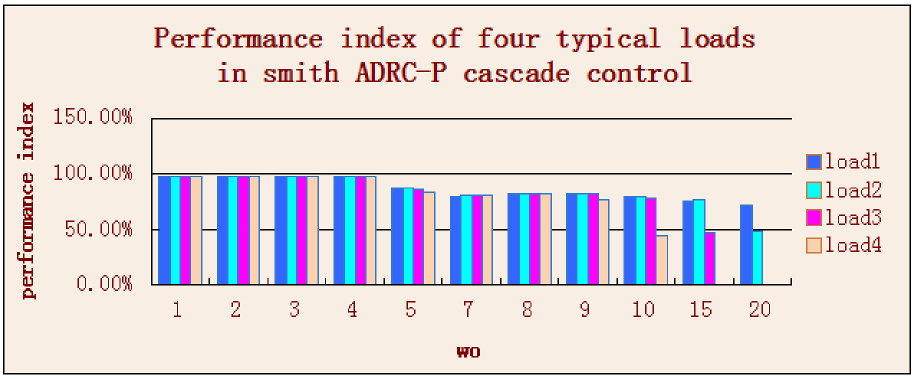

Figure 8. Performance Index of Four Typical Loads in Smith ADRC-P Cascade Control

Figure 9 and figure 10 are the results when the system is under ADRC control. Figure 9 is the variance of different loads and figure 10 is the performance index of different loads.

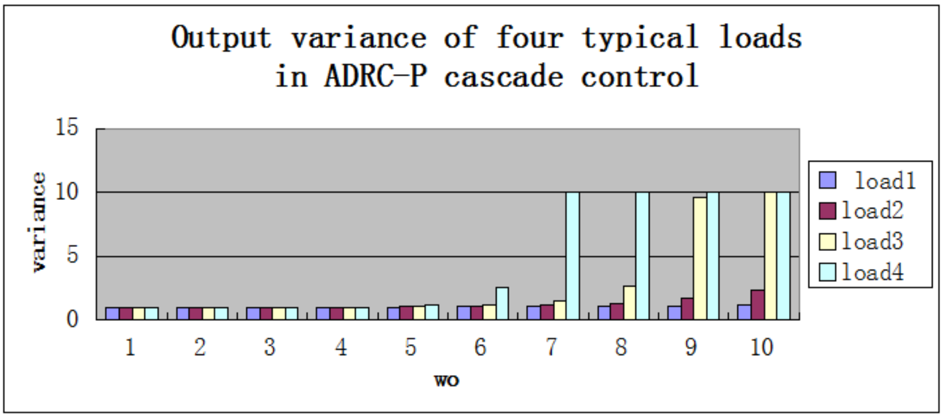

Figure 9. Output Variance of Four Kinds of Typical Load in ADRC-P Cascade Control

Similar to Figure 7, variance in load 3 and load 4 equal to 10 are also not the true case, true variance are very large. In order to make an obvious contrast, we set the variances to 10.

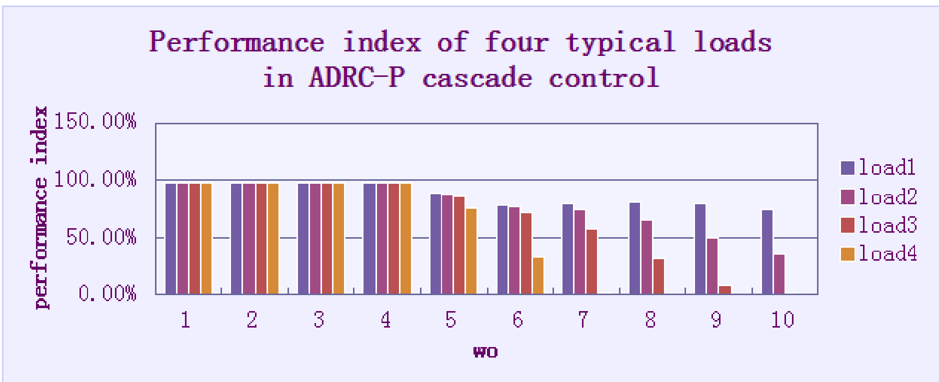

Figure 10. Performance Index of Four Typical Loads in ADRC-P Cascade Control

Form Figure 7, Figure 8, Figure 9 and Figure 10, we get the following conclusions:

(1) When wo changes between 1 and 4, the performance of the system is good. Beyond the region, the performance of the system becomes worse gradually. This is because wo is the bandwidth of the observer, normally, the larger the wo, the more accurate of the observer but the more sensitive the observer to noise. So we should make a compromise when choosing wo, not only consider the dynamic performance of the system, but also the performance of disturbance rejection. Therefore, performing the process of performance assessment can guide choosing the value of wo.

(2) Different loads have different adaptive ranges of wo. The range decreases gradually from top to bottom. It is because the inertia of the controlled object decreases gradually from top to bottom. For a first-order system, the bigger the inertia, the smaller the corner frequency, accordingly, the bandwidth of the high frequency band will increase. And high frequency band can resist noise to some extent. So, when other conditions are same, system with larger inertia has a better performance of disturbance rejection. Therefore, the adaptive range of wo is larger.

4.2. Performance Comparison of Different Control Strategies

In order to compare the performance of the two different strategies, we make a comparison of the four typical loads under ADRC control and Smith ADRC control, respectively. The results are shown as the following figures.

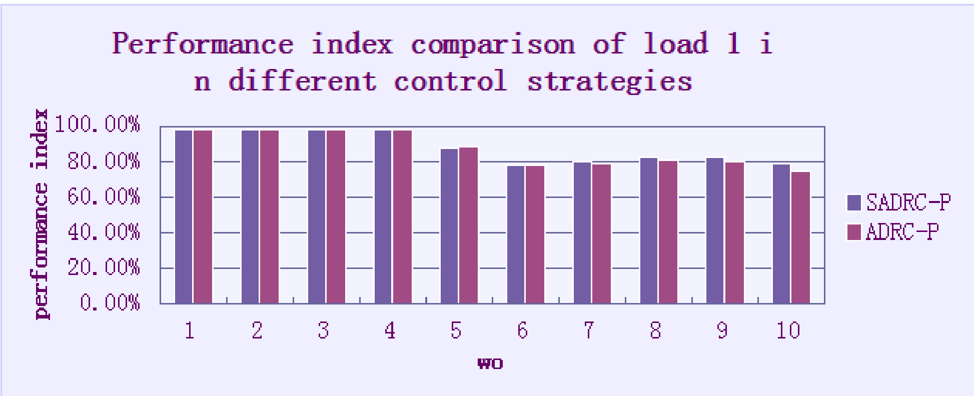

Figure 11. Performance Index Comparison of Load 1 in Different Control Strategies

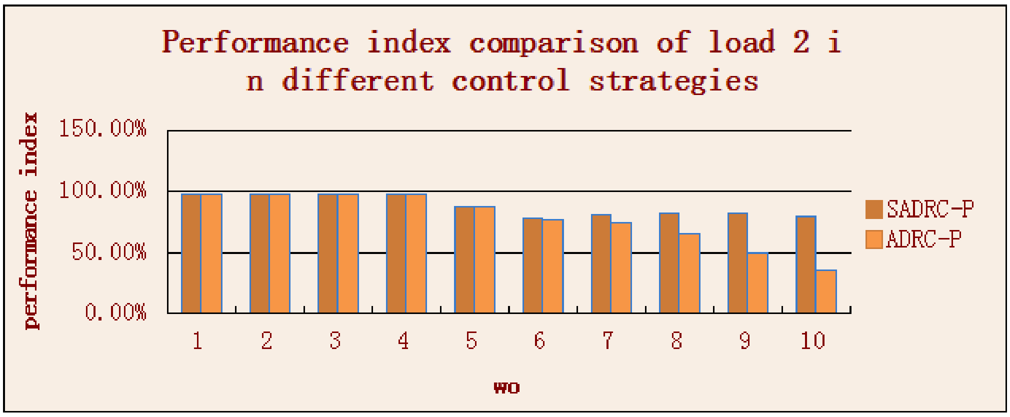

Figure 12. Performance Index Comparison of Load 2 in Different Control Strategies

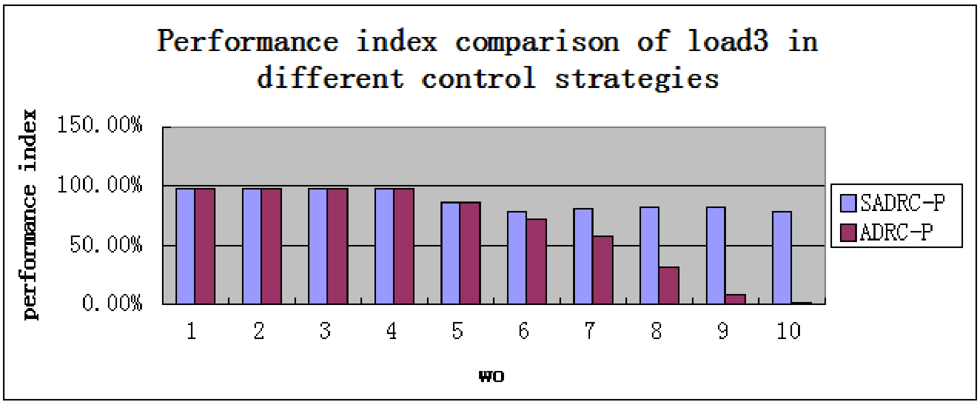

Figure 13. Performance Index Comparison of Load3 in Different Control Strategies

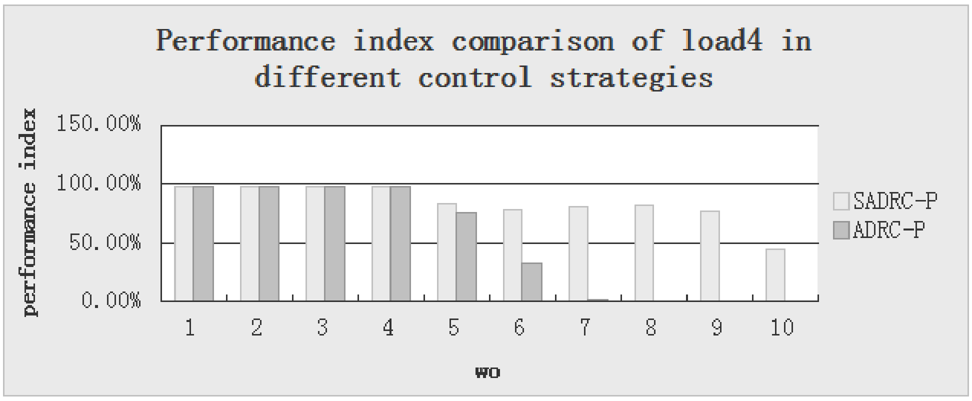

Figure 14. Performance Index Comparison of Load4 in Different Control Strategies

Form Figure 11, Figure 12, Figure 13, and Figure 14, we can conclude that: the four typical loads have a better performance when they are under Smith ADRC control than that under ADRC control. This is because adding the smith structure. Smith structure can compensate in advance. So when there is noise entering the system, the system with smith structure can control in advance, thus improving the performance of disturbance rejection of the system to some extent. Besides, we can also see that the gaps of different loads are not the same. From top to bottom, the gaps are becoming larger and larger, it is associated with the inertia of different loads. Larger inertia has a better performance of disturbance rejection.

4.3 Performance Comparison when Smith ADRC in Model Mismatch

Considering Smith structure is a model-based control structure, and is very sensitive to model mismatch. So the paper assesses the performance of the four typical loads when they are under model mismatch. Then make a comparison with the performance of model match. Comparative results are as the following tables. In these tables, "*" represents that the variance of the system is very large and the performance index is very small, close to 0. The system has a poor performance. τ is the pure delay of the system, k is the gain of the system, and T is inertia delay.

Table 3. Performance Index Comparison of Load 1 under Model Mismatch

wo	5	10	15	20	25	30
match	98.02%	75.13%	55.42%	45.30%	45.06%	45.51%
K change	96.50%	70.57%	52.62%	40.30%	23.05%	5.29%
τ change	97.44%	43.83%	3.94%	*	*	*
T change	97.99%	75.04%	55.31%	45.11%	44.89%	43.70%

Table 4. Performance Index Comparison of Load 2 Under Model Mismatch

wo	5	10	15	20	25	30
match	96.78%	74.87%	55.56%	49.97%	45.32%	40.87%
K change	88.54%	18.13%	2.72%	1.95%	*	*
τ decrease	96.08%	7.92%	*	*	*	*
τ increase	96.84%	74.55%	42.73%	3.90%	*	*
T decrease	96.65%	74.82%	55.54%	49.86%	45.28%	40.72%
T increase	96.80%	74.90%	55.42%	49.22%	44.94%	40.85%

Table 5. Performance Index Comparison of Load 3 Under Model Mismatch

wo	5	10	15	20	25	30
match	95.86%	74.58%	55.43%	49.75%	45.13%	40.69%
K change	94.96%	73.34%	55.00%	49.05%	34.08%	8.84%
τ decrease	95.84%	*	*	*	*	*
τ increase	96.82%	*	*	*	*	*
T increase	95.85%	74.59%	55.41%	49.52%	44.32%	40.39%
T decrease	95.83%	74.45%	54.35%	47.60%	24.14%	*

Table 6. Performance Index Comparison of Load 4 Under Model Mismatch

wo	5	10	15	20	25	30
match	93.16%	73.39%	54.93%	49.37%	43.98%	19.02%
K change	4.69%	*	*	*	*	*
τ decrease	91.66%	*	*	*	*	*
τ increase	92.94%	43.06%	*	*	*	*
T decrease	93.04%	56.67%	3.84%	*	*	*
T increase	93.12%	73.17%	*	*	*	*

From the above tables, we can conclude that:

(1) Performance index of the system becomes small when systems are under model mismatch. The systems have a poor performance. So the results show that smith structure is sensitive to model mismatch and smith algorithm relies badly on accurate matching model.

(2) By comparing the above tables, we can also see that the performance of disturbance rejection of the system decreases from top to bottom. This is still related to the inertia of the controlled object. The larger the inertia, the better the performance of disturbance rejection. So load 4 with the smallest inertia has the worst performance of disturbance rejection. Table 6 can obviously prove the conclusion, look at table 6, the parameters of the system only change a little, the performance of the system is close to 0.

5. Conclusion

This paper assessed the performance of four typical loads of the main steam temperature control system in thermal power plant. Comparison results show that different loads have different performance of disturbance rejection. When the load is low, the inertia of the controlled object is large, when the load is high, the inertia of the controlled object is small. Systems with lager inertia have better performance of disturbance rejection than that with smaller inertia. Simultaneously, with the same load, systems under Smith ADRC control have the better performance than that under ADRC control. Finally it also turns out that Smith algorithm is based on accurate model, when the model do not match, performance of disturbance rejection of the system will decrease.

Acknowledgements

In this paper, the research was sponsored by National Natural Science Foundation (NNSF) of China (61240037) and the Central Universities Youth Fund (11QG11).

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