

Active Disturbance Rejection Control of Thermal Power Unit Coordinated System Based on Frequency Domain Analysis

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Abstract

For the multi-input and multi-output, strong-coupling nonlinear features of coordinated system for thermal power unit, it is difficult for traditional PID coordinated control scheme to meet the power grid demand which often participates in peak regulation and frequency modulation. In this paper, inverse Nyquist array is employed to carry out frequency domain analysis of the plant model. Then Pseudo-diagonalization is used to design the static decoupling compensation matrix of the system. Above on these, the linear active disturbance rejection controller of every channel in coordinated system can be designed respectively. Dynamic coupling and system unknown parts are observed by extended state observer of ADRC and is compensated to the system in time. The simulation tests show that the disturbance rejection results of the load and the main steam pressure for the coordinated control system under LADRC is better than that of PID control.

Keywords: *thermal power unit coordinated system, linear active disturbance rejection controller, frequency domain analysis, extended state observer, pseudodiagonalization*

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1. Introduction

With the increasing demand of power and increasingly close attention to environment people pay, large thermal power units have become the main units of power grid in China because of their high efficiency, low emission, load regulating sensitive and other advantages. Since the boiler in large thermal power unit often employs the once-through boiler unit without a drum, the transition process, where water is evaporated to steam, is instant, and this makes the dynamic parameters of once-through boiler unit, such as the unit load response quality, the main steam pressure, and other parameters, present stronger coupling and stronger nonlinear properties [1-5], and these make the unit more difficult to be controlled. Therefore, in order to improve the unit load response speed and ensure the main steam pressure parameter more stable; in recent years it is becoming a hot research to master the basic characteristics of large-capacity thermal power unit, and to research an advanced control strategy for the coordinated system of the unit [6-8].

The variable parameter PID control with feed forward is widespread used in boiler turbine coordinated control system of power plant, but in this strategy, more auxiliary link and non-theoretical skills components are introduced into the system, so that the controller structure is more complex, tuning parameters of controller are serious dependent on experience, and the strategy is not easy to meet the high performance control requirements [9-10]. In modern frequency domain theory, the inverse Nyquist array (INA) method for multivariate analysis requires that the system has only the diagonal dominance, and does not need a precise mathematical model for the controlled object, but also the precompensation array optimized by the pseudo diagonalization algorithm has good decoupling effect to the system, and thus has been researched and applied to multivariable system of chemical, aerospace, power plant, and other field [11-12]. The active disturbance rejection control (ADRC) assimilating the soul of modern control theory, pioneered by Professor Jingqing Han, is a new model-independent

controller [13], which use the unique ESO to estimate the disturbance of both internal uncertainties and external disturbances in system, and automatically compensates the total disturbance, thus for nonlinear, large inertia, uncertain time-delay complex systems, this method has better control quality [14-15]. But ADRC would be improved and perfected for complex industrial process applications, and especially the numerous parameters tuning problems in ADRC have become a fundamental problem to be solved in practical application. Since feedback control structure of Linear ADRC proposed by Professor Gao [16] employs linear form, and it not only makes the theoretical analysis of ADRC further development [17-19], but also its parameters tuning is greatly simplified, and easy to be used in practice. A large number of applied researches have shown that LADRC has a strong ability to control complex nonlinear uncertain objects.

In this paper, aiming 600MW supercritical once-through boiler unit, INA method is employed to carry on the system frequency domain analysis, pseudodiagonalization method is used to conduct the pre-compensation static decoupling design for the system, and the model unknown parts of the system and dynamic disturbances are observed by ESO of ADRC, and at the same time the observed value is compensated to the system in time. The simulation results show the effectiveness of the proposed control strategy.

2. Dynamic Characteristics of Object Model

Coordinated system of the once-through boiler unit is a complicated large system. In general, the system can be seen as a three-input and three-output structure. Its input variables include the amount of fuel B , the main steam valve opening $\mu\%$ and feed water W , and the corresponding output variables contain main steam pressure P_t , the real unit power N_e , and intermediate point's enthalpy H . When the feed water of the system in accordance with certain coal-water ratio is adjusted, the system can be simplified to a two-input two-output system shown in Figure 1. Since there is a strong cross-coupling between the variables, the system also poses nonlinear and time-varying characteristics, and thus the stability margin of the system is reduced. It is difficult to achieve good control effect through using a single loop control.

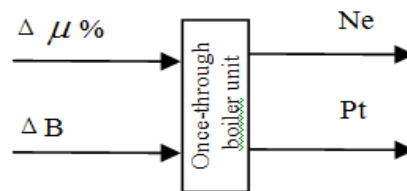


Figure 1. The simplified inputs and outputs of the power unit

In this paper, the plant we discussed is a coordinated control system of the 600MW supercritical thermal power units in Henan province. Its turbine produced by Dongfang turbine factory with signal shaft, three cylinder four exhaust, double back-pressures, pure condensing steam turbine, uses a complex operation models with variable pressure; it has an intermediate reheat, and is in supercritical conditions. The boiler made by Dongfang boiler factory is a supercritical variable parameters facility. The rated power of units is 600MW, and the object pressure before the turbine is 24.1MPa.

The experimental platform is the Star-90 system developed by North China Electric Power University with the full scope simulation about all kinds of electric power units. Based on the Star-90 simulation system, the step response data can be acquired through matlab communicating program with the simulator, and the designing model of 600MW supercritical unit at 100% load is established with the improved genetic algorithm. The transfer functions of the coordinated system are following.

$$g_{11} = \frac{6.66s(49.3s+1)}{(56.7s+1)(247.1s+1)(123.5s+1)} \quad (1)$$

$$g_{12} = \frac{1.4293(272.5s + 1)}{(175.9s + 1)(126.3s + 1)(10s + 1)} \quad (2)$$

$$g_{21} = \frac{-0.6073}{(32.7s + 1)(141.5s + 1)} \quad (3)$$

$$g_{22} = \frac{0.7282(84.9s + 1)}{(201.3s + 1)(94.66s + 1)(283.6s + 1)} \quad (4)$$

3. Frequency Domain Analysis of Coordinated System

As we all know, a precise mathematical model is required to the controlled object in the state space theory, the designed controller structure for multivariable system is quite complex, so that it is difficult to apply. In engineering, frequency domain analysis is a commonly methods of design and integration for control system. But coordinated system is a multiple-inputs and multiple-outputs coupling system, the Nyquist method often applied to analysis and optimized design a single variable, has no longer any meaning [11]. In this section, we use the inverse Nyquist array (INA) to conduct the frequency domain analysis, and adopt pseudo diagonalization to develop a decoupling design for the above system.

3.1. Multivariable Control System Architecture and Frequency Domain Analysis

Stability is one of the most important indexes for control system design. For single-input single-output (SISO) system, the characteristic roots surrounded by $(-1, j0)$ in a closed loop system can determine the distribution of its stability. But this method is not suitable for multi-input and multi-output (MIMO) system, the stability identification of multivariable system is judged through the properties of return difference determinant of the system. Multivariable system diagram is shown in Figure 2.

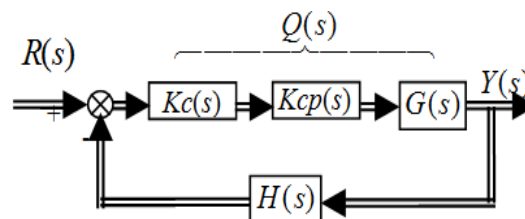


Figure 2. Diagram of multivariable control system

Where, $G(s)$ presents the controlled systems, $K_{cp}(s)$ can be seen as a pre-compensator, $K_c(s)$ is dynamic corrector, $H(s)$ is called the feedback gain matrix, $Q(s)$ represents the system forward channel matrix, then the transfer function matrix of the closed-loop system can be written as:

$$G_c = [I + Q(s)H(s)]^{-1} Q(s) \quad (5)$$

In which,

$$|D(s)| = |I + Q(s)H(s)| \quad (6)$$

The above equation (6) is called the return difference determinant of the system.

Based on the inverse Nyquist array (INA) of return difference matrix $D(s)$, engineers often use Gershgorin theorem to get the circumference number, which is surrounded with the points $(0, j0)$ by Gershgorin circles, and then observe whether $D(s)$ is diagonal dominance, and finally they can judge the stability of the system.

The inverse Nyquist array method does not require the system completely decoupled, as long as the compensated system has diagonal dominance, which makes controller design become easy.

When the number of input variables is the same as the number of output in system, assumed the number of input variable as the q -th, at $j\omega_0$ point, thus INA for the system transfer function matrix is expressed as a complex number.

$$\hat{g}_{ik}(j\omega_0) = \alpha_{ik} + j\beta_{ik}, \quad i, k = 1, \dots, q \quad (7)$$

For the values of m ($m = 1, \dots, q$), we can obtain a matrix A_m .
In which,

$$a_{il,m} = \sum_{k=1, \text{ and } k \neq m}^q [\alpha_{ik}\alpha_{lk} + \beta_{ik}\beta_{lk}], \quad i, l = 1, \dots, q \quad (8)$$

Eigenvalues and eigenvectors of the matrix A_m are computed. The eigenvectors of the minimum eigenvalues constitute a column vector of k_m , and then through all of the m values; finally we obtain the smallest feature vectors, which constitute the compensation matrix K_{cp} .

Applying above the method, in the frequency $\omega = 0$, we can get the precompensated array of K_{cp} for a boiler-turbine coordination system. Gershgorin band diagram of the system after compensated are carried out.

3.2. Diagonally Dominant Analysis of the Supercritical Unit Coordinated System

Diagonal dominance of coordination system about 600MW supercritical once-through boiler unit at 100% load is analyzed shown in Figure 3.

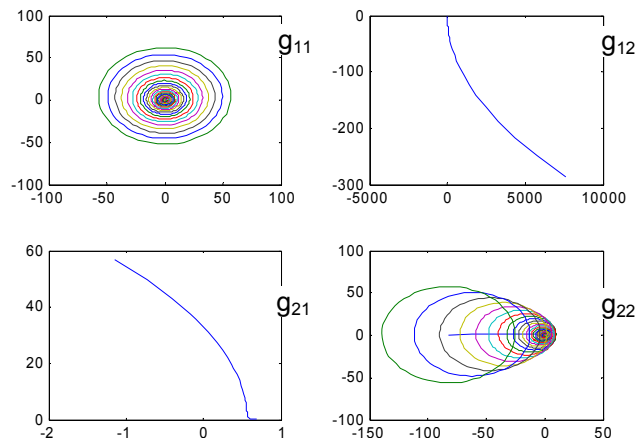


Figure 3. Diagonal dominance analysis of coordinated system about 600MW

From the above chart, we can see that, g_{11} and g_{22} in the system have surrounded the origin, so that they are non-diagonal dominance and their variables have serious coupling, Decoupling networks would need to be developed in order to design their own controller.

Decoupling design of 600MW supercritical once-through boiler unit at 100% load is shown in Figure 4. The figure shows, Gershwin Goering circles of g_{11} and g_{22} all have no longer surrounded the origin, the system has already a diagonal dominance, so the system has achieved a static decoupling, the decoupling matrix is $K_{cp} = [-0.0116 \ -0.9999; -0.9951 \ 0.0992]$.

From the above charts we can see that the open-loop transfer function matrix of boiler-turbine coordinated system has become diagonal dominance matrix, thus in the next section, we will develop two subsystems controllers by using ADRC respectively according to the design method of the single-loop controller.

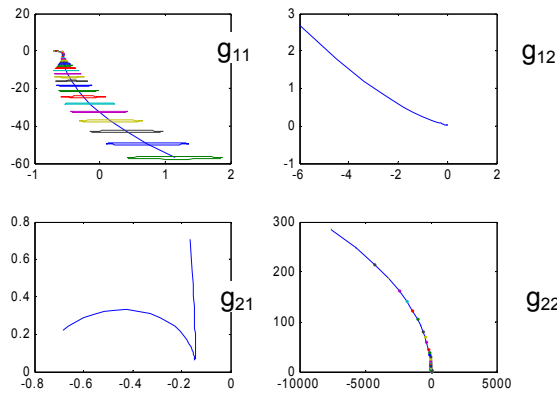


Figure 4. Precompensated decoupling design of coordinated system about 600MW

4. ADRC Design for Supercritical Unit Coordinated System

Coordinated system can be divided into two parts, turbine and boiler. Each part is a complex high-order nonlinear system, and it is very difficult to establish its accurate model. While ADRC does not demand to know the system model, we use the second order linear ADRC (LADRC) to design the turbine controller and the boiler controller.

4.1. The Structure of LADRC

LADRC controller structure is shown in Figure 5.

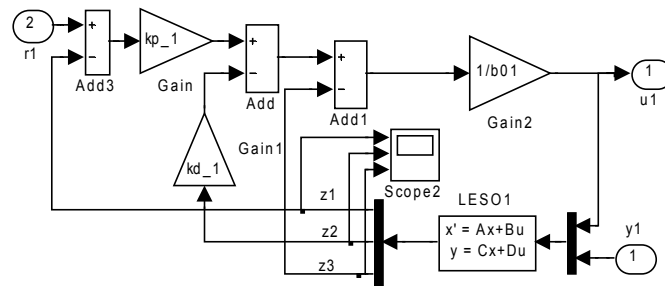


Figure 5. LADRC controller structure

In general, when the controller is designed, the part which is higher than the third-order (including third-order) in the object can be seen as uncertain part of the dynamic system, so the system can be simplified as the following form:

$$\ddot{y} = f(y, \dot{y}, w) + b_0 u \tag{9}$$

Where, u is the system input, y is the system output, w is the system unknown disturbance, f represents the system total disturbance, b_0 is the controller gain, and the state equation of the system can be expressed as the following:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = x_3 + b_0 u \\ \dot{x}_3 = h \\ y = x_1 \end{cases} \tag{10}$$

Where x_1, x_2, x_3 represents the system state variables, and $h = \dot{f}$

LESO is the extended state observer of LADRC. The inputs of the observer include output u of the controller and output y of the system. The outputs of the observer are $z=[z_1, z_2, z_3]^T$, where z_3 is the expansion of the state, represents the system total disturbance, which includes the system of external disturbances and uncertainty within the system disturbances.

Match the right observer gain, so that each observed value of LESO can track each state of the system, i.e. $z_1 \rightarrow y, z_2 \rightarrow \dot{y}, z_3 \rightarrow f(y, \dot{y}, w)$. z_3 just dynamically estimates value f . The coefficient matrix of the observer can be written respectively.

$$A = \begin{bmatrix} -\beta_1 & 1 & 0 \\ -\beta_2 & 0 & 1 \\ -\beta_3 & 0 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} 0 & \beta_1 \\ b_0 & \beta_2 \\ 0 & \beta_3 \end{bmatrix}, \quad C = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad D = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \quad (11)$$

Assuming all the poles of the observer are arranged with ω_0 , the characteristic equation for LESO is following.

$$|sI - A| = s^3 + \beta_1 s^2 + \beta_2 s + \beta_3 = (s + \omega_0)^3 \quad (12)$$

So we can obtain the following related equations,

$$\beta_1 = 3\omega_0, \beta_2 = 3\omega_0^2, \beta_3 = \omega_0^3 \quad (13)$$

Where ω_0 is called the observer bandwidth and it is the only need tuning parameters in LESO.

If the variable u is selected as the following,

$$u = \frac{-f(y, \dot{y}, w) + u_0}{b_0} \quad (14)$$

Then, the nonlinear system will become an integral series type system, namely.

$$\ddot{y} = f(y, \dot{y}, w) + bu = f - \dot{z}_3 + u_0 \approx u_0 \quad (15)$$

So we can use the "linear state error feedback (LSEF)" law to design the ideal controller. State feedback control law can be designed the following.

$$u_0 = k_p(v - z_1) + k_d(\dot{v} - z_2) = k_p(v - z_1) - k_d z_2 \quad (16)$$

Where, v is the set value.

Thus the closed-loop transfer function is described as following.

$$G_{cl}(s) = \frac{k_p}{s^2 + k_d s + k_p} \quad (17)$$

To simplify the parameters in the controller to be tuning, and ω_c is assumed as the bandwidth of the controller, so the characteristic polynomial of the controller represents as a function of ω_c , i.e:

$$s^2 + k_d s + k_p = (s + \omega_c)^2 \quad (18)$$

Where $k_p = \omega_c^2$, $k_d = 2\omega_c$, then ω_c is the only need tuning parameters in linear state error feedback (LSEF).

4.2. The design of ADRC controller of Coordinated System

Based on pseudo diagonal decoupling compensation, adrc controller of above coordinated system is built in simulink of matlab environment. In order to compare the controlled result, PID controller of the coordinated system is set commonly. The two controllers about the controlled system are shown in Figure 6. In which, the adrc controller of the coordinated system are in the upper blue dotted box, and the PID controller of the plant is in the lower pink box.

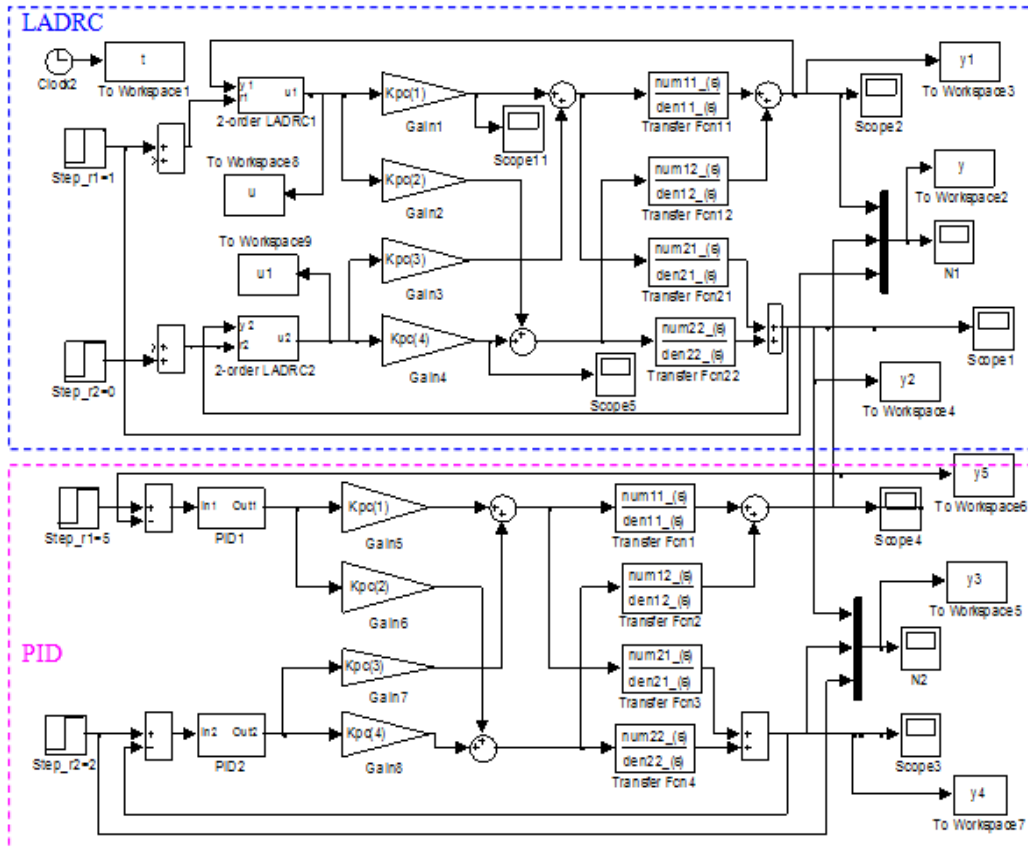


Figure 6. The control system diagrams of LADRC and PID

4.3. ADRC Simulation Experiment for Coordinated System

For a 600MW supercritical unit coordinated system at 100% load, load disturbance and the main steam pressure disturbance experiments are carried out under LADRC and PID control respectively.

In which, ADRC controller parameters are:

$$\omega_{01} = 1.89, \omega_{c1} = 0.018, b_{01} = 0.00233, \omega_{02} = 0.31, \omega_{c2} = 0.029, b_{02} = 0.00019$$

PID controller parameters are:

$$K_{p1} = 0.625, T_{i1} = 70.1, K_{p2} = 2.2751, T_{i1} = 850$$

The comparisons of system step response curves for load disturbance are shown in Figure 7.

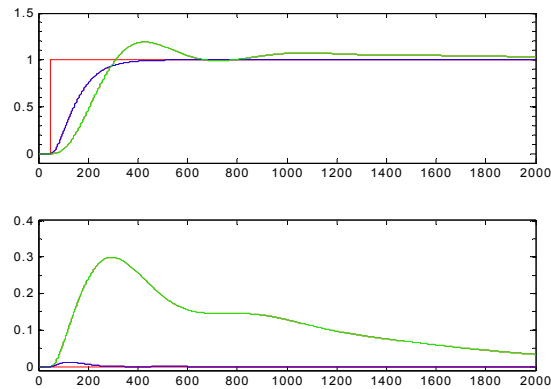


Figure 7. Comparisons of system step response curves under LADRC and PID

In Figure 7, loadstep disturbance experiment is conducted at 50s. The figure (a) is load response curve, and figure (b) is the main steam pressure response curve. The blue heavy line in the figures is under the control of LADRC response curve, the emerging green line is PID control under the response curve, and the red dashed line is the target of the system. The figures show that the plant can be seen as a single variable after the pseudo diagonalization and decoupled by ADRC, and the effect of LADRC control is much better than the effect of the PID.

The comparisons of system step response curves for the main steam pressure disturbance are shown in Figure 8.

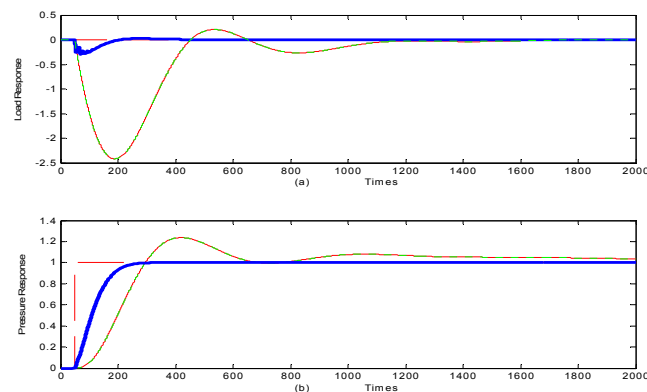


Figure 8. Main steam pressure step disturbance experiment

In Figure 8, the step disturbance experiment of the main steam pressure is conducted at 50s. The figure (a) is load response curve, and the figure (b) is the main steam pressure response curve. The blue heavy line in the figures is under the control of LADRC response curve, the emerging green line is PID control under the response curve, and the red dashed line is the target of the system. The figures show that the plant can be seen as a single variable after the pseudo diagonalization and decoupled by ADRC, and the effect of LADRC control is much better than the effect of the PID.

As we can see from the figure 8, the respond index of load and main steam pressure with LADRCs is obviously superior to that of PID.

5. Conclusion

In this paper, for coordinated system of a supercritical once-through boiler unit, frequency domain analysis is performed, steady compensation matrix is designed, and ADRC

control strategy of coordinated boiler-turbine system is established. Steady state decoupling and dynamic compensation control of the system are realized. Load step disturbance tests are carried out under PID control strategy and LADRCs control strategy respectively. The results show that the response curve controlled by LADRCs is significantly better than that of the PID controller. This strategy combined the frequency domain analysis with disturbance rejection control technology to the coordinated system in thermal power units, is a new boiler-turbine coordination control scheme, and its controller can be designed quickly and efficiently, and has less tuning parameters, is easy to be applied in engineering.

Acknowledgements

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