Research on Intelligent Adaptive Control Method for Waste Heat Power Generation Stability Problem

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ABSTRACT The effective recovery and utilization of waste heat is an important part of the energy industry chain, but the gas source of waste heat has large fluctuations and strong random frequency changes, which easily affects the quality of power generation. In order to obtain more continuous and stable electricity in the process of waste heat power generation, this paper proposes an intelligent adaptive control method. This control method decouples the variables for the characteristics of strong coupling of the waste heat power generation system, which improves the anti-disturbance performance of the system on the one hand and reduces the steady-state tracking error of the system on the other hand. Experiments show that when the gas source fluctuates, the system fluctuation rate is stable within 7%; when the set value changes, the adjustment time is within 7 s, and the overshoot is small, so the performance is better than the traditional PID control method. The intelligent adaptive control method proposed in this paper is of great significance for the future development of intelligent grid-connected power generation.

INDEX TERMS Waste heat power generation, stability, intelligent, adaptive control, decoupling.

I. INTRODUCTION
With the rapid development of society, human demand for energy is also increasing year by year. Using waste heat resources to generate electricity is an important method to alleviate the current world energy crisis. Through the operation of the power equipment, the generator is driven to generate electricity. However, due to the characteristics of many interference factors, strong coupling, and a large time lag in the waste heat power generation system, it is particularly important to maintain the stability of the power generation control system.

A. LITERATURE REVIEW
In research on the control system of waste heat power generation, the initial control strategy often adopts the PID control strategy. Zhou Xiaoran and others designed a waste heat recovery control system based on the Rankine cycle. The control object of this system is temperature, and the control method used is PID control. The control strategy is simple and can basically meet the system requirements. However, the control system is difficult to control more accurately and quickly and needs to be optimized [1]. To compensate for the shortcomings of the PID control system, a closed-loop PID algorithm is used in the air compressor waste heat recovery system to maximize the heat collection by limiting the oil temperature of the oil-water heat exchanger. However, because the system is affected by multiple disturbance factors, the closed-loop PID control algorithm does not have high control precision for the target variable, and the adaptability and stability of the system are not ideal [2]. To improve the shortcomings of the closed-loop PID algorithm, Kuang Lei et al. adopted the fuzzy PID control algorithm to strengthen the controllability of the waste heat application in the waste heat recovery system of the air compressor. Although this algorithm can achieve maximum heat...
collection, it cannot achieve constant temperature control on the waste heat application side, and it is difficult to solve the problem of system coupling [3]. Yupeng Wang et al. designed and implemented a neural PID controller to control the outlet temperature of the evaporator in an ORC system for waste heat recovery. Compared with the traditional PID control strategy, this method can better predict the dynamic response and has strong robustness to parameter changes and external disturbances [4]. Zhang Wen et al. studied the dynamic performance of an internal combustion engine-organic Rankine cycle combined system in an internal combustion engine waste heat recovery system. A control method combining closed-loop proportional-integral and feedforward control is adopted, and the response time and overshoot of PI control are estimated and compared with feedforward control alone. The results show that the closed-loop system can enhance the stability of the input and output of the control system [5].

The results based on the World Harmonized Transient Cycle (WHTC) show that the designed closed-loop PI control has a shorter response time and better tracking ability in dynamic processes. Pang Kuo Cheng et al. used the simulation platform to compare the VFD control strategy and the pump curve control strategy of the organic Kenlang cycle. The results show that the two control strategies have different effective intervals, but the stability of the recovery system cannot be guaranteed [6]. Zhao Mingru proposed a map-based feedback closed-loop control algorithm in the waste heat recovery system of an internal combustion engine. To make the control more convenient, this method reduces the order of the initialized organic Rankine cycle model and constructs an algorithm fusion controller for the nonlinear model. The control effect of the algorithm has been greatly improved [7].

Zhang et al. proposed a multivariable control scheme for an ORC system for waste heat recovery by combining a linear quadratic regulator with a PI controller in a simulated environment. This solution is equivalent to a linear quadratic integral controller with feedforward, and simulation experiments show that this method has a good response to load tracking and disturbance rejection [8]. A model predictive controller was implemented on a small ORC system, two variants of MPC (linear and nonlinear) were implemented on a real-time embedded platform, and the performance of the controller was compared with that of a traditional PID controller [9]. The linear model predictive controller (LMPC) has better control stability for control variables and is superior to the PID controller in response time, overshoot, oscillation and stability time. The nonlinear model predictive controller (NMPC) strategy can achieve smoother, safer and more efficient operation to achieve similar or better tracking performance under a lower control workload [10].

B. RESEARCH GAP AND MOTIVATION

In summary, there is much room for improvement in the control field of waste heat power generation, especially the stability of the control system. The existing control methods tend to produce fluctuations in airflow within the power generation unit when executing control commands, making it difficult to return the system to the preset rated state with a faster rotational speed and smaller overshoot when fluctuations in the waste heat gas source occur. At the same time, fluctuations in the air supply will cause fluctuations in the output power, which, if not controlled, can lead to overloading of the waste heat recovery unit during energy conversion. The connected electrical equipment will also be affected. Therefore, in order to reduce the energy loss in the waste heat recovery process and enhance the stability of the waste heat recovery system in operation, it is more critical to study the stability of the control system while the structure of the waste heat recovery device is being updated.

C. CONTRIBUTION

The intelligent adaptive control method proposed in this paper combines the coupling analysis, control and identification of controlled objects based on the use of roots power machine [11], aiming at the nonlinear, multivariable, multimodel and strong coupling characteristics of waste heat power generation control systems to realize more accurate control of systems with unknown variables or time-varying systems. Compared with the existing control methods, the intelligent adaptive control method avoids the contradiction between rapidity and overshoot, the simple signal processing process, and the easy oscillation of the system in the traditional PID control method, and retains the advantages of closed-loop PI control. It achieves a shorter response time and more sensitive tracking performance under system fluctuations. The experimental results show that if this intelligent adaptive control theory is applied to the existing control system of waste heat power generation, the stability of the waste heat recovery system and the response rotational speed of the control system can be improved in the case of multi-parameter interaction and fluctuation of the gas source. The control method in this paper is of great significance to the continuous and stable production of waste heat power generation, the improvement of power generation and automation level, and the intelligent control of the production process.

D. PAPER ORGANIZATION

The main contents of this paper are as follows: The second part is the research on the parameter coupling mechanism of the waste heat power generation control system. Aiming at the complex relationship between parameters such as temperature, pressure, flow rate and the rotational speed of the roots power machine in the waste heat power generation system, the analysis and modeling are carried out, and the coupling relationship model and control process model of the variables of the waste heat power generation control system are initially obtained. This provides the basis for the design of the control method. The third part is the decoupling analysis of the system coupling variables and the design of the intelligent adaptive control method. Specifically, the “intelligent adaptive control method” referred to in this paper refers to the closed-loop adaptive decoupling control strategy under...
the nonlinear multivariate multimodel. Finally, the parameter stability calculation is carried out to prove that the stability requirements are met. The fourth part uses simulation technology to compare the anti-interference ability and tracking ability of the new control strategy of the roots waste heat power generation system with the traditional PID control strategy. The characteristics of the control effect of the two control strategies are obtained, and the availability of the new control strategy in the waste heat power generation system is determined. The fifth part builds the experimental platform and designs the human-computer interaction system for the test. The test process includes the fluctuation interference test and the set value change test, and the collected data are compared with the data obtained by PID control under the same conditions to verify the significant advantages of the new control strategy in waste heat power generation system.

II. VARIABLE ANALYSIS AND CONTROL PROCESS OF WASTE HEAT POWER GENERATION CONTROL SYSTEM

The waste heat power generation system referred to in this article is an energy conversion and recovery system with a roots power machine as the source power machine. The main components include the base, control system operation cabinet, roots power machine, electric regulating valve, shut-off valve, power generator, speed sensor, flowmeter, thermometer, filter, pressure gauge and connecting devices between various components. The waste heat enters the chamber inside the roots power machine through the intake pipe, and the blades of roots power machine rotor will rotate and do work under the expansion of waste heat gas and pressure. The output shaft of the rotor of the roots power machine is connected with the rotating shaft of the generator through the coupling and other components, and the generator is driven to generate electricity through the connected rotating shaft. The overall structure of the roots-type waste heat power generation device is shown in Figure 1.

![Figure 1. Structure diagram of roots type waste heat power generation device.](image)

The waste heat power generation system involves many changes in the working process. When any variable of the system changes, other variables will be affected. To keep the rotational speed of roots generator stable, that is, to ensure the stability of the power generation system, it is necessary to study and analyze these input and output variables and their coupling relationship model.

A. INPUT AND OUTPUT VARIABLES OF THE SYSTEM

With the deepening of research, the relationship contained in the controlled system becomes increasingly complex, and there is often more than one pair of variables that need to be controlled. Because of the mutual coupling relationship, there are increasing amounts of multiple-input multiple-output systems (MIMO systems). Control methods suitable for single-input single-output systems cannot be implemented in MIMO systems.

The output rotational speed of the roots power machine is directly related to the output of the electrical energy of the system, so the key to the quality of waste heat power generation lies in the stable control of the output shaft rotational speed of the roots power machine. This output is affected by the flow of the working fluid, the temperature and pressure of the working fluid at the inlet, the temperature and pressure of the outlet, and the slagging, ash, and scaling conditions on the inner cavity of the power machine.

The roots-type waste heat power generation control system is a five-input single-output system. The input consists of five variables: flow, inlet temperature, inlet pressure, outlet temperature, and outlet pressure. The control system needs to collect these five input variables and analyze and calculate them according to the deviation between the output variable and the expected value, then obtain the electrical signal for adjusting the electric control valve, and finally transform it into the adjustment of the rotational speed of the roots power machine. The controlled variable of the roots-type waste heat power generation control system is the rotational speed of the roots power machine, that is, the output variable of the system.

B. VARIABLE COUPLING ANALYSIS

The coupling relationship of variables is inseparable from the working process. This section combines the normal working state of the roots-type waste heat power generation control system to analyze the relationship between the input variables and output variables. The coupling relationship between variables lays the foundation for the following model analysis [12].

In the normal working process of the roots power machine, the internal changes are very complex, and there are more or less coupling relationships between each variable. When the opening of the electric regulating valve changes, the flow through the roots power machine will change, and the change in the flow will directly affect the rotational speed of the roots power machine. When the pressure difference between the air inlet and the air outlet occurs, it will directly affect the flow rate, which in turn affects the rotational speed of the roots power machine. When the temperature difference between the air inlet and the air outlet changes, it will directly affect the pressure difference between the air inlet and the
air outlet and then indirectly affect the flow rate and the rotational speed of the roots power machine. A schematic diagram of the variable coupling relationship in the roots-type waste heat power generation control system is shown in Figure 2.

C. MULTIVARIATE AND MULTIMODEL COUPLING RELATIONSHIP ANALYSIS

To better explore the work characteristics of the roots-type waste heat power generation control system, it is necessary to model and analyze the variables and coupling relationships involved in the work process of the system. Therefore, we first consider the working process under the ideal state based on the control variable method. The relationship between the power and speed of the generator can be expressed as:

\[ P = \frac{n}{9550} M \]  

(1)

In the formula, \( P \) is the rated power of the generator, \( n \) is the rated speed, and \( M \) is the rated torque. According to Formula (1), the relationship between the power of the generator and the rotational speed is a linear relationship in an ideal state; that is, the relationship between the rotational speed of the roots power machine and the power of the generator is also a linear relationship.

1) TEMPERATURE AND PRESSURE MODEL

\[ pV = n_0RT \]  

(2)

When the pressure of the waste heat working fluid is stable, the model can also be simplified to a steady flow state, and the working fluid gas at this time is regarded as an ideal state gas and processed by Formula (2). Then, after the roots power machine does work, the state of the waste heat working medium at the air inlet and air outlet can be expressed as:

\[ \frac{Q_{\text{in}}t}{T_{\text{in}}} = \frac{Q_{\text{out}}t}{T_{\text{out}}} + C_1 \]  

(5)

In the formula, \( C_1 \) is a constant related to the energy consumption of the roots power machine. Under actual working conditions, the pressure of the waste heat working medium will deviate from the calculation results, so this model can be used as a relationship similar to the actual working conditions in the actual application process.

2) TEMPERATURE AND FLOW MODEL

When the temperature of the waste heat working fluid is constant, the relationship between gas pressure and flow rate can be expressed by Bernoulli’s equation [14]:

\[ p + \rho gh + \frac{1}{2} \rho v^2 = E \]  

(7)

In the formula, \( g \) is the acceleration of gravity, and the unit is m/s\(^2\); \( h \) is the height of the fluid, and the unit is m; \( v \) is the flow velocity of the fluid, and the unit is m/s; and \( E \) is a constant related to energy.

When the Bernoulli equation is applied, the Mach number (Ma) of the fluid needs to satisfy Ma < 0.3; the expression of the Mach number during the flow of the waste heat working medium in the device is:

\[ Ma = \frac{v}{a} \]  

(8)

where \( a \) is the speed of sound in m/s. The working fluid velocity in the pipeline is 55.97 m/s, which meets the Mach number requirement.
Therefore, the control process transfer function model of the mechanical transmission link belongs to a pure lag link. The adjustment process belongs to an inertial link, and the internal signal amplification belongs to a proportional link, according to the working characteristics of the electric control valve, the electric regulating valve to adjust the valve opening. According to the above analysis of each part of the control module, the transfer function of each control module is obtained. After connecting them in series, the overall control process transfer function of the roots-type waste heat utilization system can be obtained. Its overall control process transfer function is shown in Figure 5.

By analyzing the Bernoulli equation, the gravitational potential energy of the gas can be neglected; then, Equation (7) can be expressed as:

$$ p + \frac{1}{2} \rho v^2 = E \tag{9} $$

When the waste heat gas flows through the roots power machine to do work, the state change of the working fluid at the inlet and outlet can be expressed as:

$$ p_{in} + \frac{1}{2} \rho v_{in}^2 = p_{out} + \frac{1}{2} \rho v_{out}^2 + C_3 \tag{10} $$

In the formula, the relationship between flow rate and flow velocity can be expressed by Equation (10). $C_3$ is a constant related to the energy consumption of the roots power machine, which can be specifically expressed as the energy consumed by the unit volume of waste heat gas in the process of doing work by the roots power machine.

**D. ANALYSIS OF THE OVERALL CONTROL PROCESS MODEL OF THE SYSTEM**

After analysis, the control process structure of the roots-type waste heat power generation control system is shown in Figure 3.

The rotational speed setting value is set by the human-computer interaction system, and the controller will adjust the opening of the electric regulating valve according to the rotational speed setting value, control the flow rate of the waste heat working medium in the pipeline, and then adjust the flowrate by controlling the RPM of the engine.

When the rotational speed of the roots power machine changes, the controller will send a regulating signal to the electric regulating valve to adjust the valve opening. According to the working characteristics of the electric control valve, the internal signal amplification belongs to a proportional link, the adjustment process belongs to an inertial link, and the mechanical transmission link belongs to a pure lag link. Therefore, the control process transfer function model of the electric regulating valve can be obtained, and the model block diagram is shown in Figure 4.

Here, $K_0$ is the amplification factor of the electric control valve, $T_0$ is the time constant of the electric control valve, $D_1(s)$ is the external temperature difference feedback signal, and $D_2(s)$ is the external pressure difference feedback signal.

According to the control model, its transfer function can be expressed as:

$$ G_0(s) = G_1(s)[1 + D_1(s) + D_2(s)] \tag{11} $$

$$ G_1(s) = \frac{K_0}{T_0s + 1} e^{-\tau_0s} \tag{12} $$

According to the analysis of the working characteristics of the roots power machine, the transfer function of the roots power machine can be expressed by Formula (13):

$$ G_2(s) = \frac{K_1}{T_1s + 1} e^{-\tau_1s} \tag{13} $$

Without considering the sensor signal error, the speed sensor can accurately express the speed it detects, so the transfer function of the speed sensor can be expressed as:

$$ G_3(s) = \frac{Q(s)}{P(s)} = K_2 \tag{14} $$

In the formula, $Q(s)$ is the sensor signal, and $P(s)$ is the output speed function. The resulting transfer function result is a time-independent constant.

According to the above analysis of each part of the control module, the transfer function of each control module is obtained. After connecting them in series, the overall control process transfer function of the roots-type waste heat utilization system can be obtained. Its overall control process transfer function is shown in Figure 5.

Therefore, after connecting the above parts in series, the transfer function of the rotational speed adjustment process of the roots-type waste heat utilization system can be expressed as:

$$ G(s) = \frac{K[1 + D_1(s) + D_2(s)]}{(T_0s + 1)(T_1s + 1)} e^{-(\tau_0 + \tau_1)s} \tag{15} $$

$$ K = K_0K_1K_2 \tag{16} $$

![FIGURE 3. Control process diagram.](image-url)

![FIGURE 4. Transfer function model of the electric control valve control process.](image-url)

![FIGURE 5. Transfer function model of the whole control process of the system.](image-url)
where $s$ represents the Laplace operator; $T_0$ and $T_1$ are the oscillation periods; $\tau$ is the process lag time constant; and $K$ is the process steady-state gain coefficient.

### III. RESEARCH ON INTELLIGENT ADAPTIVE CONTROL METHOD

On the basis of the coupling analysis of the multi-variable and multivariable and multimodel of the waste heat power generation control system in the second part, this part will conduct a closed-loop decoupling analysis of the system according to the nonlinear characteristics of the waste heat power generation control system and design a new type of intelligent adaptive control method [15]. The new intelligent adaptive controller designed in this paper can handle the strong coupling between parameters and use the multi-model system obtained from the previous disassembly to design the waste heat power generation system, so that the design of this controller is more in line with the characteristics of the waste heat power generation control system, and it is the first time to apply this control method to the study of the stability of the waste heat power generation system.

The design of this control method is very dependent on the overall process of the waste heat power generation device and the work characteristics of the roots power machine. The thermodynamic properties of this system are obviously nonlinear, so the original control system should be expressed as a nonlinear system. Let $r$ and $y$ be the input and output of the system, respectively. The system equation of the nonlinear system can be expressed as:

$$M(z^{-1})y(t+a) = N(z^{-1})r(t) + v[X(t)]$$ (17)

Equation (17) is the system equation of the nonlinear system represented by the matrix equation, where $X(t)$ is the data vector of the nonlinear system composed of the input sequence and the output sequence, $v[\cdot]$ represents that the data vector is a higher-order nonlinear vector function, and $a$ is the time delay of the nonlinear system.

### A. ONE-STEP-AHEAD OPTIMAL DECOUPLING CONTROL LAW

To carry out the closed-loop decoupling design, according to the transfer function model of the control system, the coupling effect of the input channel of the control system on the output channel is regarded as the interference source, and the coupling effect is compensated by using the feedforward method. The feedforward compensation method that realizes the control can compensate for the coupling component when it is generated. Compared with the general feedback control, the feedforward compensation can be compensated in a timelier manner, and the feedforward compensation cannot be affected by the time delay of the control system.

The input parameter matrix function of the nonlinear system can be expressed as:

$$N(z^{-1})r(t) = \overline{N}(z^{-1})r(t) + \overline{N}(z^{-1})r(t)$$ (18)

where $\overline{N}(z^{-1})$ is a diagonal matrix, which represents the relationship between input parameters and output parameters on the main channel of the control system.

Another matrix is as follows:

$$\overline{N}(z^{-1}) = N(z^{-1}) - \overline{N}(z^{-1})$$ (19)

This indicates the coupling relationship between other different channel variables in the control system. According to the nonlinear control system, the one-step ahead optimal performance index is introduced into the control system and has the following weighting form:

$$J'(t) = \frac{1}{2} \left[ \|L(z^{-1})y(t+d) - O(z^{-1})u(t+d) + K(z^{-1})v[X(t)]\|^2 + W'(z^{-1})r(t) + S(z^{-1})r(t)\|^2 \right]$$ (20)

where $u(t)$ is the bounded reference input vector, $L(z^{-1})$, $O(z^{-1})$, $K(z^{-1})$, and $W(z^{-1})$ are weighted polynomial matrices of one-step ahead optimal performance indicators; $S(z^{-1})$ is also a weighted polynomial matrix, but the main diagonal elements of this weighting polynomial matrix are zero. The optimal control law is the controller that minimizes the performance index of Equation (20). The output of this auxiliary system can be defined as:

$$\beta(t+a) = L(z^{-1})y(t+a)$$ (21)

In addition, the input to the auxiliary system can be defined as:

$$\alpha(t+a) = O(z^{-1})u(t+a) - W(z^{-1})r(t)$$

$$W(z^{-1}) = \begin{bmatrix} E_0N_0 + E_0C + K_0C \\ E_0 + E_0 + S(0) + S(0) \end{bmatrix}$$ (23)

$$S(z^{-1}) = \begin{bmatrix} E_0N_0 + E_0C + K_0C \\ E_0 + E_0 + S(0) + S(0) \end{bmatrix}$$ (24)

Here, the partial derivative of the high-order nonlinear vector function in the system to the input variable vector is a constant matrix, and matrix $C$ is a constant matrix. In addition, $K_0$ is a constant matrix term of $K(z^{-1})$. $E(z^{-1})$ can be determined by the Diophantine equation [16]:

$$L(z^{-1}) = E(z^{-1})M(z^{-1}) + z^{-a}G(z^{-1})$$ (25)

$E_0$ is the constant matrix term of $E(z^{-1})$, and it can be known by calculation that $F_0=P(0)$. In the formula, $G(z^{-1})$ is a diagonal matrix polynomial, and its order is one order lower than the matrix polynomial of the input parameters.

At this time, to solve the optimal control law with the original performance index (20) as the minimum, it can now be equivalently transformed with the minimum performance index for the auxiliary system defined...
by Equations (21) and (22). The performance index formula of the system is:

\[
J(t) = \left\| L(z^{-1})y(t + a) - O(z^{-1})u(t + a) + W(z^{-1})r(t) + S(z^{-1})v(t) + K(z^{-1})v[X(t)] \right\|^2
\]  

(26)

After solving, the one-step-ahead optimal weighted closed-loop decoupling control law that can minimize the performance index formula of the system is:

\[
[E(z^{-1})N(z^{-1}) + W(z^{-1})]r(t) + [E(z^{-1})N(z^{-1}) + S(z^{-1})]v(t) = O(z^{-1})u(t + a) - G(z^{-1})y(t) - [E(z^{-1}) + K(z^{-1})]v[X(t)]
\]  

(27)

At this time, for the input variables of the system, it is necessary to ensure that the vector \( r(t) \) exists. Therefore, the weighted polynomial matrix in the performance index equation needs to satisfy:

\[
detL(0) \neq 0, \ det[E_0N_0 + W(0) + S(0)] \neq 0
\]  

(28)

At this point, by substituting the optimal decoupling control law into the nonlinear system, we obtain:

\[
[L(z^{-1})N(z^{-1}) + M(z^{-1})]y(t + a) = M(z^{-1})O(z^{-1})u(t + a) - [M(z^{-1})K(z^{-1}) + L(z^{-1})]v[X(t)]
\]  

(29)

In addition, the following can be obtained by calculation:

\[
[L(z^{-1})N(z^{-1}) + W(z^{-1})]y(t + a) = N(z^{-1})O(z^{-1})u(t + a) + [W(z^{-1})N(z^{-1}) - N(z^{-1})S(z^{-1})]y(t) + [W(z^{-1}) - N(z^{-1})K(z^{-1})]v[X(t)]
\]  

(30)

At the same time, to make the nonlinear system have closed-loop stability, the weighted polynomial matrices \( L(z^{-1}), S(z^{-1}) \), and \( W(z^{-1}) \) must also meet the following conditions:

\[
det[L(z^{-1})N(z^{-1}) + M(z^{-1})]y(t + a) \neq 0, |z| \geq 1
\]  

(31)

When the higher-order nonlinear vector function in a nonlinear system is small, it can be regarded as a bounded perturbation. The control law at this time can be obtained by the linear method:

\[
[E(z^{-1})N(z^{-1}) + W(z^{-1})]y(t) = O(z^{-1})u(t + a) - G(z^{-1})y(t)
\]  

(32)

B. IDENTIFICATION EQUATION

In the intelligent adaptive control algorithm, the control system needs to have an identification process. The identification process refers to determining a model equivalent to the system under test from the known models through the input data and output data collected by the system.

The parameter matrix of the nonlinear system can be identified by the recursive method. For nonlinear systems, using equation (25), the identification equation of intelligent adaptive control can be calculated [17], [18], [19]:

\[
L(z^{-1})y(t + a) + H(z^{-1})r(t) + E(z^{-1})v[X(t)] = \phi(t + a)
\]  

(33)

After simplification, it can be written as:

\[
\phi(t + a) = \Phi^T X(t) + U[X(t)]
\]  

(34)

\[
D(z^{-1}) = E(z^{-1})N(z^{-1})
\]  

(35)

Therefore, Equations (27) and (32) can be written as:

\[
\Phi^T X(t) + \delta[X(t)] = O(z^{-1})u(t + a) - [W(z^{-1}) + S(z^{-1})]r(t) - K(z^{-1})v[X(t)]
\]  

(36)

\[
\Phi^T X(t) = O(z^{-1})u(t + a) - [W(z^{-1}) + S(z^{-1})]r(t)
\]  

(37)

C. INTELLIGENT ADAPTIVE CONTROL METHOD BASED ON NONLINEAR MULTIVARIATE AND MULTIMODEL

The intelligent self-adaptive control method is a control method for nonlinear multivariable and multimodel. In the roots-type waste heat power generation system, the control model can be switched intelligently according to the working conditions. The output variables of the control system can track the changes of the pre-specified bounded input variable settings, while also reducing the effects of coupling effects between different parameters [20], [21], [22], [23].

For the identification equation of Equation. (34), its linear prediction model can be defined as follows:

\[
\hat{\phi}_1(t + a) = \Phi_1(t)^T X(t)
\]  

(38)

The linear model-based estimation of the parameter matrix at time \( t \) can be corrected online by the following identification methods:

\[
\hat{\Phi}_1(t) = \text{proj}[\Phi_1(t)]
\]  

(39)

\[
\hat{\Phi}_1(t) = \hat{\Phi}_1(t - a) + c_1(t)X(t - a)p_1(t)^T
\]

\[
\frac{1}{1 + X(t - a)^TX(t - a)}
\]  

(40)

\[
p_1(t) = \phi(t) - \hat{\phi}_1(t)
\]  

(41)

If \(|p_1(t)| > 2A, c_1(t)=I; \text{otherwise}, c_1(t)=0. \text{A is the known upper bound of } ||U[X(t)]||, \text{and } A>0.\)

For the identification equation of Equation. (34), its neural network nonlinear prediction model can be defined as follows:

\[
\hat{\phi}_2(t + a) = \Phi_2(t)^T X(t) + \hat{U}[X(t)]
\]  

(42)

The estimation of the parameter matrix based on the nonlinear model at time \( t \) can be similar to the estimation of the linear model. The identification method is as follows:

\[
\hat{\Phi}_2(t) = \text{proj}[\Phi_2(t)]
\]  

(43)

\[
\hat{\Phi}_2(t) = \hat{\Phi}_2(t - a) + \frac{e(t)X(t - a)p_2(t)^T}{1 + X(t - a)^TX(t - a)}
\]  

(44)

\[
p_2(t) = \phi(t) - \hat{\phi}_2(t)
\]  

(45)
If \( |p(2)| > 2B, \varepsilon(t) = 1 \); otherwise \( \varepsilon(t) = 0 \). \( B \) is the known upper bound of \( |U[X(t-1) - \hat{U}[X(t-1)]| \). For \( \hat{U}[X(t-1)] \), that is:

\[
\hat{U}[X(t)] = NN[\delta(t), X(t)] \tag{46}
\]

where \( NN[\cdot] \) represents the neural network structure. \( X(t) \) is a vector composed of the input and output of the nonlinear system and is the input vector of the neural network here. \( \delta(t) \) is the estimated matrix of the ideal weight matrix at time \( t \). In this formula, \( \delta(t) \) is bounded.

According to Equation (37) and the deterministic equivalence principle, the adaptive closed-loop decoupled controller \( r_1(t) \) based on linear model estimation can be expressed as:

\[
\Phi_1(t)^T X(t) = O(z^{-1})u(t + a) - [W(z^{-1}) + S(z^{-1})]p_1(t) \tag{47}
\]

According to Equation (36) and the deterministic equivalence principle, the neural network adaptive closed-loop decoupling controller \( r_2(t) \) based on nonlinear model estimation can be expressed as:

\[
\Phi_2(t)^T X(t) + \hat{U}[X(t)] = O(z^{-1})u(t + a) - [W(z^{-1}) + S(z^{-1})]p_2(t) - \hat{e}[X(t)] \tag{48}
\]

The weighted polynomial matrix is selected according to the analysis of the weighted polynomial matrix above. \( \hat{e}[X(t)] \) is calculated as follows:

\[
\hat{e}[X(t)] = [W(z^{-1})/\hat{H}_2(t, z^{-1})] \hat{U}[X(t)] \tag{49}
\]

The switching criterion function can be represented by the following function:

\[
J_k(t) = \sum_{l=a}^{t} c_k(l)[|p_k(l)|^2 - 4M^2] + b \sum_{l=a}^{t} [1 - c_k(l)] |p_k(l)|^2 \tag{50}
\]

\[
c_k(t) = \begin{cases} 1, \text{if } |p_k(l)| > 2A \\ 0, \text{else} \end{cases} \tag{51}
\]

In the formula, if \( |p_k(l)| > 2A, c_1(t) = 1 \); otherwise, \( c_1(t) = 0 \). \( n \) is a positive integer, and \( b \geq 0 \) is a constant, which can be determined in advance. The value of \( k \) is 1 or 2. When the value is 1, it means linearity; when the value is 2, it means nonlinearity.

Adaptive control is embodied in that, at each moment, the value of \( J_k(t) \) when \( k = 1 \) and \( 2 \) is compared, the minimum value is taken, and then the adaptive decoupling controller \( r_1(t) \) or \( r_2(t) \) corresponding to this value is selected. Then apply it to the controlled system.

The system structure of the intelligent adaptive control method based on nonlinear multivariable and multimodel is shown in Figure 6.

The workflow of the intelligent adaptive control system can be specifically summarized as shown in Figure 7.

1. Establish a nonlinear system;

2. Determine the weighted polynomial matrix. Make \( L(z^{-1}), W(z^{-1}), O(z^{-1}), S(z^{-1})K(z^{-1}) \) meet the requirements of equation (28);

3. Collecting output quantities and creating a data vector;

4. Calculate the discrimination errors;

5. Compare \( J_1(t) \) and \( J_2(t) \) to select the minimum value and choose the corresponding decoupling controller \( r_n(t) \) to apply it to the nonlinear system;

6. Let \( t = t + 1 \), and then return to step (3).

D. STABILITY ANALYSIS OF THE INTELLIGENT ADAPTIVE CONTROL SYSTEM

When the weighted polynomial matrix satisfies the conditions of Equations (28) and (31) and the upper bound of the nonlinear term is known, we can set:

\[
\hat{\Phi}(t) = \Phi(t) - \Phi \tag{52}
\]

According to the calculation process of the prediction model identification method, it can be known that:

\[
\|\hat{\Phi}(t)\|^2 \leq \|\Phi(t - a)\|^2 - \frac{c(t)[|p(t)|^2 - 4A^2]}{2[1 + X(t - a)^T X(t - a)]} \tag{53}
\]

Since \( |p(t)| > 2A, c(t) = 1 \); otherwise, \( c(t) = 0 \). Thus, \( \{(i + a)|/2 = 0, \ldots, a - 1\} \) is a monotonically non-increasing sequence, so \( \hat{\Phi}(t) \) is bounded.

The following is true:

\[
\lim_{n \to \infty} \sum_{t=a}^{n} \frac{c(t)[|p(t)|^2 - 4A^2]}{2[1 + X(t - a)^T X(t - a)]} < \infty \tag{54}
\]

\[
\lim_{t \to \infty} \frac{c(t)[|p(t)|^2 - 4A^2]}{2[1 + X(t - a)^T X(t - a)]} = 0 \tag{55}
\]

According to Formula (43) and Formula (46), the following can be obtained:

\[
p_1(t + a) = \varphi(t + a) - \hat{\Phi}_1(t)^T X(t) \tag{56}
\]

According to Formula (47) and Formula (50), the following can be obtained:

\[
p_2(t + a) = \varphi(t + a) - \hat{\Phi}_2(t)^T X(t) - \hat{U}[X(t)] \tag{57}
\]
Combining the deterministic equivalence principle, we can obtain the following at any time $t$:

$$\bar{p}(t + a) = p_1(t + a) + e[X(t)]$$  \hfill (58)

Therefore, at any time, the identification error of the Intelligent adaptive control system is $p_1(t + a)$ or $p_2(t + a)$, and $||X(t-a)||$ is bounded.

According to the function switching criterion, the second term of $J_k(t)$ is bounded, and then according to Equation (46), it can be obtained that $J_1(t)$ is bounded. For $J_2(t)$, if $J_2(t)$ is bounded, according to the switching function criterion, it can be known that the identification error $p(t)$ of this system satisfies Equation (47).

If $J_2(t)$ is unbounded, since $J_1(t)$ is bounded, there is a time $t_0$ such that when time $t$ is greater than or equal to $t_0$, $J_1(t) \leq J_2(t)$ is satisfied. According to the switching function criterion, when the time $t$ is greater than or equal to $t_0+1$, the identification error $p(t)$ of this system also satisfies the equation.

In summary, regardless of whether it is bounded, the system identification error satisfies Equation (47), so $X(t-a)$ is bounded, and the system is closed-loop stable.

### IV. SIMULATION ANALYSIS

To test the performance of the intelligent adaptive control method based on the roots-type waste heat power generation system, the PID control method previously studied and the control method studied in this paper are used for simulation comparison to test the two control methods in the control effect when encountering continuous small-amplitude fluctuations from the outside world and changes in the set value. The system dynamic model was constructed in a MATLAB/Simulink environment [24].

In the process of PID control system regulation of the roots power machine, to achieve the desired control effect, the PID parameters $K_p$, $T_i$, $T_d$ need to be adjusted, and other parameters need to be taken according to the actual production operation and relevant reference materials. In MATLAB, the root trajectory function rlocus and rlocfind commands are used to determine $K_p$, $T_i$, $T_d$ according to Ziegler-Nichols critical proportional coefficient method, and the Ziegler-Nichols PID parameters rectification table is shown in Table 1, $K_k$ is the crossing gain and $T_k$ is the critical oscillation period of the system.

At the critical stable speed, the parameters of the PID controller are adjusted as follows: $K_p = 0.98$; $T_i = 150.00$; $T_d = 39.00$.

The simulation comparison experiment scheme of small amplitude fluctuation interference is to add a step signal or a ramp signal with a lower peak value at a certain time point. The simulation comparison test scheme when the set value changes is to increase the step signal of a certain value at the set time point. Finally, the control effect of the control system is analyzed according to the simulation graph.
In this paper, the control method of this paper is compared with the PID control method on MATLAB/Simulink software simulation platform. The overall structure of the simulation comparison experiment is shown in Figure 8. The values of the devices in the figure will vary as the simulation experiment requires.

The upper part of the figure is an intelligent adaptive control method based on nonlinear multivariable and multimodel with five inputs and one output, and the lower part is a traditional PID control method with a single input and a single output [25]. By changing the magnitude and time of the step signal, the roots-type waste heat power generation system can be simulated under the actual working conditions when the fluctuation or set value changes. The main indicators of the simulation comparison are based on the overshoot and adjustment time, corresponding to the fluctuation range and adjustment time in the performance indicators.

A. ANTI-INTERFERENCE ABILITY TEST UNDER SMALL FLUCTUATION INTERFERENCE

The unstable phenomenon of waste heat gas sources in actual situations can be simulated through low-amplitude step signals and ramp signals. The rotational speed of the simulation test is set to 400 r/min, and two small-amplitude interference signals with opposite directions are added through the controls in the simulator to simulate the increase in gas volume and the gas volume of the gas source in the actual working conditions of the roots-type waste heat utilization system.

After simulation, the obtained results are shown in Figure 9.

The black curve \( r(t) \) in the figure represents the fluctuation applied to the system, the red curve \( y(t) \) represents the rotational speed response curve of intelligent adaptive control, and the blue curve \( u(t) \) represents the traditional PID control rotational speed response curve. At 15 s and 35 s, two fluctuating signals with increasing gas volume and decreasing gas volume were added. The magnitude of the signal is not fixed, indicating random small-amplitude fluctuations. The simulation results show that both control methods can stabilize the rotational speed to the set value, but the time for the two to stabilize is different. The PID control method stabilizes the system within 4 s on average, and the control method has an obvious overshoot phenomenon, while the intelligent adaptive control method stabilizes the system in an average of 1.5 s, and the control has almost no overshoot.

In contrast, the adjustment time of intelligent adaptive control is less than a half of that of PID control, and there is almost no fluctuation. Therefore, the intelligent adaptive control method has a faster adjustment rotational speed and higher stability in the face of small fluctuations.

B. TEST OF THE ABILITY TO TRACK THE CHANGE OF THE SET VALUE

The change in the rotational speed setting value is realized by the step signal. The initial rotational speed of the system is set to 400 r/min, and then a step signal is added at 10 s, and the rotational speed is set to 300 r/min. When it reaches 30 s, a step signal is added again, and the rotational speed is set to 500 r/min. The tracking ability of the two control methods is tested when the set value changes.

After simulation, the result obtained is shown in Figure 10.

The black curve \( r(t) \) in the figure represents the set value of the system rotational speed, the red curve \( y(t) \) represents the rotational speed response curve under intelligent adaptive control, and the blue curve \( u(t) \) represents the rotational speed response curve under traditional PID control. The rotational speed was set to 300 r/min at 10 s, the intelligent adaptive control method remained stable within 2 s, and the overshoot did not exceed 1%. The stabilization time of the PID control method is 5 s, and the overshoot is 6%. When the time reaches 30 s, the rotational speed is set to 500 r/min, the intelligent adaptive control method remains stable at 2.5 s, and the overshoot also does not exceed 1%. The stabilization time of the PID control method is 6 s, and the overshoot is 5%.

The simulation results show that the adjustment time of the intelligent adaptive control method is shorter, and its rotational speed adjustment effect is obviously better than that of the PID control method. In addition, by comparing the overshoot of the two control methods, we can see the overshoot of the PID control method. It is 5 to 6 times that of the intelligent adaptive control method. Therefore, the tracking ability of the intelligent adaptive control method has obvious advantages compared with the PID control method.

V. ACTUAL TESTING AND DATA ANALYSIS

A. EXPERIMENTAL SCHEME DESIGN

For the experiment to verify whether the controller can keep the system to maintain a stable rotational speed in the case of small fluctuations in the roots-type waste heat power generation control system, according to the performance index
of the rotational speed, the parameter index of the rotational speed during the experiment is set to 300 r/min. The small fluctuations during the experiment are random fluctuations, which can be simulated by changing the size of the intake air, that is, by manually fine-tuning the opening of the gas tank valve during the experiment. After the experiment, the change curve of the rotational speed during the experiment is drawn, and whether the deviation of the rotational speed fluctuation meets the parameter index of the rotational speed fluctuation range $-7\% \sim +7\%$ is analyzed.

For the experiment to verify whether the controller can respond in time and make accurate adjustments when the set value of the roots-type waste heat power generation control system changes, according to the performance index of the rotational speed, the adjustment parameter of the rotational speed in the experiment is set as 300 r/min and 400 r/min. To improve the accuracy of the experiment, it is necessary to verify not only the effect when the rotational speed is increased but also the effect when the rotational speed is decreased. Therefore, in the experiment, the initial rotational speed was set to 300 r/min, and then the rotational speed was adjusted to 400 r/min. After the equipment was stabilized, the rotational speed was set to 300 r/min. After the experiment, we analyze the data, compare whether the adjustment time meets the rotational speed adjustment time performance index of 7 s, and analyze the overshoot to verify whether the test process is stable.

**B. EXPERIMENTAL PLATFORM DESIGN**

In this paper, artificial equipment is used to replace the waste heat generated in actual enterprises. Therefore, under laboratory conditions, compressed air with similar air source properties is selected as the air source to replace the waste heat generated in the actual production process. The power of the generator is inconvenient for data monitoring. Therefore, under laboratory conditions, an eddy current brake is used to replace the generator, and the eddy current brake is used to provide a load to the roots-type waste heat power generation control system, which also makes the monitoring data more accurate.

The overall structure of the experimental platform of the roots-type waste heat utilization system is shown in Figure 11.

1) **INTAKE AND OUTTAKE SECTIONS**

The data monitoring points of temperature, pressure and flow are at the inlet and outlet, so flow meters, thermometers and pressure gauges are installed on the inlet and outlet pipelines, respectively. After design, the instrument installation of the intake pipeline and the exhaust pipeline is shown in Figure 12.

The thermometer and the pressure gauge are connected by threaded type in the intake and outtake pipelines. The flow sensor is a Hongqi Instrument brand vortex flowmeter, which is installed in a flanged wafer on the intake and outlet pipelines. The valves on the pipeline are a ZDLP-16C-type electric regulating valve and a J41H-16C-type manual stop valve.

2) **MAIN PART**

The work part of the experimental device is shown in Figure 13(a), and the detection instrument is shown in Figure 13(b). The air inlet and outlet of the roots power machine are connected to the intake pipeline and the exhaust pipeline, respectively. The output shaft of the roots power machine is connected to the speed sensor through coupling, and the other end of the speed sensor is connected to the eddy current brake through coupling. The speed range is 300-500 r/min, and the power range is below 10 kW. Therefore, the speed sensor is a CGQY torque speed sensor and
TR-4D torque speed power measuring instrument produced by HT-SAAE. The brakes are also WZ-20 eddy current brakes and WLK controllers produced by HT-SAAE. The eddy current brake generates a load equivalent to the generator of the same power through the setting of the controller to simulate the situation in which the roots-type waste heat power generation control system drives the generator to work under actual working conditions.

3) CONTROL SYSTEM PART
The controller of the experimental platform control system is an embedded control system based on STM32 series microprocessors. Between the controller, the sensor and the controlled device, the conventional RS485, RS232 and standard current signal communication methods are used for data acquisition and output control. The display of data and the operation of the control system are realized through the MCGS touch screen. The operation and control part of the experimental platform is shown in Figure 14.

4) HUMAN-COMPUTER INTERACTION SYSTEM
The data processing of the roots-type waste heat power generation control system is realized by the microcontroller, the data are saved on the touch screen, and the data can be downloaded to a U disk. The human-computer interaction system is realized through the touch screen. The specific human-computer interaction interface is shown in Figure 15. The overall connection relationship of the control system is shown in Figure 16.

C. EXPERIMENTAL RESULTS AND DATA ANALYSIS
1) SMALL FLUCTUATION INTERFERENCE TEST
To verify the working state of the roots-type waste heat power generation control system under actual working conditions
and the performance of the intelligent adaptive control method, according to the experimental scheme of this paper, the rotational speed of the roots power machine is set at 300 r/min. Then, the air supply is manually adjusted to apply small fluctuation disturbances to the system. After the experiment, the system is updated, and the PID control method is used to carry out the same experiment as the experimental control.

During the experiment, several sets of data were sampled, and the rotational speed data were used to draw the rotational speed curve under PID control and the rotational speed curve under intelligent adaptive control.

Several sets of tests were carried out under PID control, and the rotational speed curve drawn by some of the test data is shown in Figure 17.

The blue curve in the figure represents the rotational speed curve under PID control, the red curve represents the deviation range of the rotational speed fluctuation, and the black curve represents the set value of the rotational speed. From Figure 17, it can be roughly seen that the rotational speed of the roots power machine is maintained within the rotational speed fluctuation deviation range most of the time, but there are still many time points where the rotational speed has exceeded the rotational speed fluctuation deviation range. Under PID control, the fluctuation range of the rotational speed crosses the boundary line of the fluctuation deviation, and the fluctuation range is large.

After statistical analysis, the data information is shown in Table 2.

From the statistical analysis in Table 2, it can be seen that the average value of the rotational speed is very close to 300.00 r/min, indicating that the overall rotational speed fluctuates around the set value. However, the maximum deviation and the minimum deviation of the rotational speed exceeded the fluctuation range of the parameter index $-7.00\% \sim +7.00\%$, which does not meet the requirements. In addition, the variances of the rotational speed of these 10 groups of data are all above 200.00, which also shows that the fluctuation of the rotational speed under PID control is very obvious, and the stability of the system is insufficient.

Several sets of tests were carried out under intelligent adaptive control, and the rotational speed curve drawn by some test data is shown in Figure 18.

The blue curve in the figure represents the rotational speed curve under intelligent adaptive control, the red curve represents the deviation range of the rotational speed fluctuation, and the black curve represents the set value of the rotational speed. From Figure 18, it can be roughly seen that...
the rotational speed of the roots power machine is always within the deviation range of rotational speed fluctuations and does not exceed the data points of the parameter indicators. Moreover, it can be clearly seen that under intelligent adaptive control, the size of the deviation is obviously smaller than the requirements in the performance index.

After statistical analysis, the data information is shown in Table 3.

From the statistical analysis in Table 3, it can be seen that the average value of the rotational speed under intelligent adaptive control is approximately 300.00 r/min, indicating that the overall rotational speed also fluctuates up and down from the set value. The maximum deviation and minimum deviation of the rotational speed are within 5.00 r/min, which is obviously smaller than the fluctuation range of the parameter index \(-7.00\%\) to \(+7.00\%\). Moreover, the variance of these data is small, which also shows that under intelligent adaptive control, the rotational speed fluctuation is weak, and the system stability is strong.

Through the statistics of Figure 17 and Figure 18, the control effects and characteristics of the two control methods under the disturbance of small amplitude fluctuations are analyzed.

In order to make the comparison between the two control methods more obvious, the rotational speed curves of the two control methods are shown in a graph, as shown in Figure 19.

The blue curve shows the rotational speed curve under PID control, the orange curve shows the rotational speed curve under intelligent adaptive control method, and the black curve shows the rotational speed setting value. It is obvious that the rotational speed under intelligent adaptive control is closer to the rotational speed setting value of 300.00 r/min, and the error is smaller. This indicates that the intelligent adaptive control method is more effective than the PID control method when the rotational speed is disturbed by small fluctuations.

The rotational speed adjustment comparison in Table 4 can be obtained by comparing the rotational speed data of the two control methods.

By comparing the data in the table, it can be seen that the difference between the average rotational speed of the two control methods and the set rotational speed is not large, indicating that the rotational speed of the two control methods changes around the set value and meets the most basic control requirements.

The average maximum deviation of the PID control method is 5.4 times higher than that of the intelligent adaptive control method, and the maximum deviation also exceeds 7.00\% of the average rotational speed, which is about 8.11\%, and does not meet the parameter index requirements. In contrast, the average maximum deviation under the intelligent adaptive control method is within 2\%, which meets the parameter index requirements, and the stability is improved by about 6\% compared with the PID control method. In addition, the average variance of the rotational speed under the PID control method is 30 times higher than that under the intelligent adaptive control method, indicating that the intelligent adaptive control method has more effective anti-interference capability than the PID control method in the face of fluctuations in the gas source.

2) SET VALUE CHANGE TEST

The tracking performance test is achieved by changing the set value. First, the equipment is stabilized at 300.00 r/min, and then the rotational speed is adjusted to 400.00 r/min through the human–machine interface. After the rotational speed is stable for a period of time, the rotational speed is adjusted to 300.00 r/min. The rotational speed data of the two control methods are tested when the set value changes. The rotational speed curve under PID control is shown in Figure 20.

![FIGURE 20. (a) Rotational speed curve 1 under PID control. (b) Rotational speed curve 2 under PID control.](image-url)

The black curve in the figure represents the set value, and the blue curve represents the rotational speed. The figure shows that when the set value changes, the rotational speed of the roots power machine fluctuates greatly, the overshoot is close to 50 r/min, and the adjustment time is also relatively long.

After statistical analysis, the data information is shown in Table 5.

It can be seen from the statistical data that the peak overshoot values under PID control all exceed 30.00 r/min, which obviously exceed the fluctuation range required by the control

### Table 4. Comparison table of rotational speed regulation under wave disturbance.

| Control Method       | Average rotational speed (r/min) | Mean maximum deviation (r/min) | Average variance |
|----------------------|----------------------------------|-------------------------------|-----------------|
| Intelligent adaptive | 300.01                           | 4.50                          | 6.87            |
| PID control          | 300.07                           | 24.35                         | 211.36          |
The black curve in the figure represents the set value, and the blue curve represents the rotational speed. It can be seen from the figure that when the set value changes, the rotational speed of the roots power machine smoothly follows the set value change, and there is no large overshoot after the set value is exceeded. From the speed change to the speed trend, the time taken for stabilization is significantly shorter compared to the PID control method.

After statistical analysis, the data information is shown in Table 6.

It can be seen from the statistical data that the peak value of the overshoot does not exceed 10.00 r/min under intelligent adaptive control, which meets the fluctuation range required by the control index. From the change of the set value to the stabilization of the rotational speed, the adjustment time of the intelligent adaptive control method is approximately 5 s, which meets the adjustment time index requirement of 7 s. It is about 3 s shorter than the PID control method, and the advantage is more obvious.

The control effects of the two control methods when the set values are changed are analyzed by the statistics in Figure 20 and Figure 21, respectively. To make the comparison more obvious, the results of the two control methods are shown in one figure, as shown in Figure 22.

The blue curve shows the rotational speed under the PID control method, the orange curve shows the rotational speed under the intelligent adaptive control method, and the black curve shows the set value of the rotational speed. It can be seen that the rotational speed overshoot is smaller and the adjustment time is shorter under the intelligent adaptive control method. This indicates that the intelligent adaptive control method is more effective than the PID control method when the rotational speed setting value changes.
By comparing the rotational speed data of the two control methods, the rotational speed adjustment comparison table shown in Table 7 can be obtained.

By comparison, the adjustment time of the PID control method in the experiment is significantly longer than 7 s, which exceeds the time period of the performance index. Due to the stability of the PID control method, the overshoot of the PID control method has significantly exceeded the rotational speed fluctuation range of 7%. In contrast the intelligent adaptive control method has a significantly faster regulation speed, with an improvement of about 41.70%, and the overshoot is all within a 7% rotational speed fluctuation. It is verified that the intelligent adaptive control method has better tracking performance when the setting value of the roots-type waste heat power generation control system changes.

VI. CONCLUSION

Aiming at the problem that the waste heat fluctuates more in the gas source fluctuation and the frequency change is not fixed, which makes the stability of the system difficult to maintain during operation, a new control method for the waste heat power generation system is designed to greatly improve the system stability and achieve better effect.

In this paper, the control variable method is used to analyze the relationship between different parameters, and the coupling relationship model and control process model of the control system are designed, which provides the basis for the design of the control method. Then, according to the characteristics of strong coupling of waste heat power generation system, research on intelligent adaptive control based on nonlinear multivariable and multmodel is established, and the control method is designed so that the control system can meet the control index requirements of root-type waste heat power generation system. The new control strategy designed in this paper is simulated and compared with the traditional PID control strategy to verify the outstanding advantages of the new control strategy in this paper. Finally, an experimental platform was built for experimental testing. The experiments respectively test the control effects of the intelligent adaptive control method and the PID control method when the small fluctuation disturbance and the rotational speed setting value change. The experimental results show that the intelligent adaptive control method satisfies the performance indicators, and the control effect is better than the PID control method, which verifies the control effect of the control method and the availability in the roots-type waste heat utilization system. It is confirmed that the application of this control method to the waste heat power generation control system can improve the stability of the system. This promotes the development of waste heat control systems.

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