Adaptive Fault-tolerant Control of Gas-cooled Microreactor Based on Model Reference Adaptive Control

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Abstract

As a novel mobile nuclear power supply, the gas-cooled microreactor (GMR) has important application value in power supply for remote areas and microgrids. However, under typical fault scenarios such as reactivity disturbance, precooler/intercooler flow loss, and main circuit helium leakage, traditional PID control struggles to ensure the safe and stable operation of the GMR. To address this challenge, this paper designs an adaptive fault-tolerant control system based on model reference adaptive control (MRAC) to maintain consistent performance during both normal and faulty conditions. Simulations show that the adaptive fault-tolerant control has better performance than traditional PID control. The results demonstrate that the adaptive fault-tolerant control method can enhance the adaptability and control performance under fault conditions.

Full Text

Preamble

Shaanxi Key Laboratory of Advanced Nuclear Energy and Technology, School of Nuclear Science and Technology, Xi'an Jiaotong University, Xi'an, 710049, China; China Nuclear Power Engineering Co., Ltd., Beijing, 100840, China Abstract: As a novel mobile nuclear power supply, the gas-cooled microreactor (GMR) has important application value in power supply for remote areas and microgrids. However, under typical fault scenarios such as reactivity disturbance, precooler/intercooler flow loss, and main circuit helium leakage, traditional PID control struggles to ensure the safe and stable operation of the GMR. To address this challenge, this paper designs an adaptive fault-tolerant control

system based on model reference adaptive control (MRAC) to maintain consistent performance during both normal and faulty conditions. Simulations show that the adaptive fault-tolerant control has better performance than traditional PID control. The results demonstrate that the adaptive fault-tolerant control method can enhance the adaptability and control performance under fault conditions. Keywords: Gas-cooled microreactor; Model reference adaptive control; Fault-tolerant control; Overshoot

1 Introduction

Responding to growing market demands for enhanced nuclear safety, flexibility, and multifunctional applications, small modular reactors (SMRs) have emerged as a key research focus in the global nuclear industry. SMRs offer distinct advantages through their high safety standards, modular design, and broad application prospects [1]. A gas-cooled microreactor (GMR) based on a prismatic high-temperature gas-cooled microreactor is proposed for a movable nuclear power supply. The modular high-temperature gas-cooled reactor with passive safety is combined with a direct Brayton cycle energy conversion system. Its potential applications include supplies of competitive electricity and heat for remote and off-grid communities, as well as industrial locations. Microreactors have the potential to provide economic and social value in new markets [2]. Because of the structural characteristics of its high-temperature gas-cooled reactor integrated with Brayton cycle, the GMR shows strong coupling and strong nonlinearity. Traditional control system can only guarantee the control effect around the chosen working point, and it does not consider the harsh and unattended working environment. In this environment, the possibility of fault or failure is significantly increased. As highly complex energy systems, nuclear reactors may suffer from risks during operation. In the event of a failure, power outages and equipment damage may result and in the worst case, radioactive material leakage can happen and lead to severe threats to personnel safety and the ecological environment. To avoid the loss caused by failure, adaptive fault-tolerant control is necessary.

With the improvement of industrial automation level, the application of fault-tolerant control in nuclear power plants is gradually increasing, and the design of control law has become a research hotspot [3]. Eryurek et al. proposed a fault-tolerant control and diagnosis system (FCDS) for nuclear power plants and it was applied to the steam generator feedwater regulation system. The FCDS can automatically switch control modes in the event of sensor failures or controller abnormalities. A fuzzy logic controller demonstrates superior stability and disturbance rejection capability during transient responses. This validates the effectiveness of the parallel redundancy architecture in avoiding unplanned shutdowns and maintaining the stability of the steam generator level [4]. Zhao et al. designed a water level fault-tolerant control system for the steam generator feedwater system based on back propagation neural network. The fault-tolerant control is realized using the method of control law reconstruction, which improves the reliability of the system [5]. The basic principle of adaptive fault-tolerant control is to utilize the idea of parameter self-adaptation to design an adaptive control law to estimate fault parameters online and provide the information required by the adaptive controller. Such methods seldom suffer from misdetections, omissions, and diagnostic delays, and have a relatively simple structure. Ahmed-Zaid et al. first applied the adaptive technique to the problem of fault-tolerant control, which led to a relatively rapid development of adaptive fault-tolerant control and was applied to reconfiguration controllers [6]. Dong used nonlinear adaptive control in both modular high-temperature gas-cooled reactors as well as pressurized water reactors to design the power control system. The effectiveness of the control system was proved by simulation verification [7]. Cheng et al. designed a dynamic compensation controller with integrity for closed-loop system actuator faults so as to ensure system stability [8]. Gao et al. designed an output feedback control method based on an adaptive neural network for linear, nonlinear systems, and uncertain time delay systems, based on an adaptive method for different modes of actuator, sensor, and system faults. Adaptive state feedback and dynamic output feedback fault-tolerant control systems were designed [9]. Model-reference adaptive control (MRAC) is one of the adaptive fault-tolerant control methods. Nguyen et al. designed an MRAC-based adaptive compensation control term to compensate for uncertain model parameters was proposed [10]. Santanu et al. combined model-free control (MFC) with model reference adaptive mechanisms to propose an intelligent proportional-integral-derivative controller that did not require prior knowledge of the system or complex tuning, enabling efficient and robust tracking control of a class of dynamic systems [11]. Xiao et al. designed a PID controller based on model reference adaptive control in the voltage control system of one-way and three-islanded microgrids. MIT rules were used as adaptive laws. According to the difference between the reference model output and the actual output, the PID controller output was adjusted in real time through the adaptive law. The simulation test showed that compared with the traditional PID control, the voltage control based on MRAC could reduce the influence of external disturbance, improve the robustness of the system, and achieve high precision control [12].

The GMR serves as a mobile power source for remote areas and emergency scenarios, and often operates unattended. Owing to its highly coupled and nonlinear nature, traditional PID control struggles to maintain system stability when faced with reactivity disturbances, abnormal coolant flow, or helium leakage in the main circuit. Such faults may lead to severe consequences, including power oscillations and temperature runaway. To overcome these challenges, this paper proposes an adaptive fault-tolerant control with MRAC. The advantage of MRAC lies in its ability to define desired dynamic characteristics through a reference model and employ adaptive laws to adjust controller parameters in real time, thereby compensating online for performance degradation caused by system faults. Simulation results demonstrate that the MRAC is shown in Fig. 2.1, GMR consists of the reactor and energy conversion system. The reactor system consists of fuel assemblies, control rods, casings, and other components. The energy conversion system includes a helium turbine, generator, compressor precooler, low-pressure compressor, compressor intercooler, and high-pressure compressor [13]. The nonlinear dynamic model and its control system have been designed [13]. They are implemented in MATLAB/Simulink and introduced in this section.

2.1 Nonlinear Dynamic Model of GMR

Based on the mass, energy, and momentum conservation equations, the nonlinear dynamic model of the reactor system is established. The reactor system is shown in Fig. 2.2 and divided into six coolant nodes, one fuel node, and one reflector layer node. The coolant nodes are for the inlet header, back reflector, reflector channel, front reflector, coolant channel, outlet header, fuel and reflector [14].

[FIGURE:2.2] Reactor system nodes

The reactor power is calculated using the point reactor kinetics equations with six groups of delayed neutrons [15].

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$$\frac{dn}{dt} = \frac{\rho - \beta}{\Lambda} n + \sum_{i=1}^{6} \lambda_i C_i$$

$$\frac{dC_j}{dt} = \frac{\beta_j}{\Lambda} n - \lambda_j C_j, \quad j = 1, 2, \dots, 6$$

where n is the number of neutrons in the reactor, ρ is the reactivity, β is the delayed neutron fraction, β_i is the ith group delayed neutron fraction, Λ is the prompt neutron life time, s, λ_j is the jth group delayed-neutron precursor decay constant; and C_j is the jth group delayed-neutron precursor concentration, where $j = 1, 2, \dots, 6$.

Considering control rods, fuel temperature, moderator feedback, and reflector temperature reactivity feedback, the net reactivity is calculated as

$$\rho = \rho_{rod} + \alpha_f (T_f - T_{f0}) + \alpha_m (T_m - T_{m0}) + \alpha_r (T_r - T_{r0})$$

where ρ_{rod} is the control rods reactivity, α_f is the fuel temperature feedback coefficient, α_m is the moderator temperature feedback coefficient, and α_r is the reflector temperature feedback coefficient.

The control-volume division of the energy conversion system is shown in Fig. 2.3, which includes the pipes, helium turbine, low-pressure compressor, high-pressure compressor, generator, compressor precooler, compressor intercooler, permanent magnet synchronous generator, external load and heat sink, as shown in Fig. 2.3.

[FIGURE:2.3] The control-volume division of the energy conversion system.

The dynamic model of the helium turbine and compressor system is established according to the characteristics of each component. Based on the equations of mass conservation, energy conservation, and momentum conservation, nonlinear dynamic models of the generator, precoolers, intercoolers and pipes are established.

The thermohydraulic model of the helium flow loop is described by the mass conservation equation, the energy conservation equation, and the momentum conservation equations:

$$A\Delta z\frac{d\rho}{dt} = W_i - W_o$$

$$A\Delta z\frac{d(\rho h)}{dt} = W_i h_i - W_o h_o + Q$$

$$\frac{dW}{dt} = \frac{A}{\Delta z}(P_i - P_o) - \frac{f\Delta z W^2}{2D\rho A^2} - \rho g A\sin\theta$$

where P_o is outlet helium pressure, Pa; P_i is the inlet helium pressure, Pa; W_i is inlet helium mass flow, kg/s; A is area, m^2; ρ_o is outlet helium density, kg/m^3; h is enthalpy, J/kg; Δz is the channel length, m; ρ_i is the inlet helium density, kg/m^3; h_i is the inlet helium enthalpy, J/kg; h_o is the outlet helium enthalpy, J/kg; Q is the helium absorbs heat, J/s; θ is the angle between the control volume and the horizontal line; W_o is the outlet helium mass flow, kg/s; g is the gravitational acceleration, m/s^2; f is the flow resistance coefficient; D is the hydraulic diameter of control volume, m.

2.2 GMR Control Systems

Based on the established linear dynamic model, after analyzing the dynamic characteristics of the system, the established GMR control system includes a speed control system based on coordinated control, a reactor outlet helium temperature control system, the precooler/intercooler outlet temperature control system, an electric power control system and a rotor speed control system. Aiming at the problems of large parameter fluctuation and long setting time of the traditional control system of GMR under load change, a speed control system based on coordinated control is established. The coordinated control system has been established and is shown in Fig. 2.4.

Fig. 2.4 Speed control system based on coordinated control. As is shown in Fig. 2.4, the coordinated speed control system employs two distinct deviation signals: turbine inlet helium pressure deviation and rotor speed deviation. These signals are sent to the coordination control module to derive gains for different deviation conditions based on data fusion. The signal is further served as input to the filling/evacuating controller. The coordinated control module adjusts the proportion of the two deviations in the filling and evacuating control by judging the size of the helium pressure deviation at the turbine inlet. When the absolute value of the pressure deviation is greater than 0.25 MPa, the speed deviation signal does not participate in the filling control at this time. The adjustment of the system is completed by the pressure deviation signal; when the absolute value of the pressure deviation is 0.01 MPa and 0.25 MPa, both the pressure deviation and the speed deviation are involved in the filling control. With the decrease of the pressure deviation, the weight of the pressure deviation signal in the fusion signal gradually decreases, and the weight of the speed deviation signal in the fusion signal gradually increases. When the absolute value of the pressure deviation is less than 0.01 MPa, the pressure deviation is no longer involved in the filling control. At this time, the filling control depends entirely on the rotor speed deviation. When the rotor speed deviation is 0, the filling controller no longer operates, and the rapid and error-free adjustment of the rotor speed in a wide range of variable working conditions is realized.

Fig. 2.5 Reactor outlet helium temperature control system. As is shown in Fig. 2.5, the reactor outlet helium temperature control system modifies the reactivity of control rods to track changes in the reactor outlet helium temperature setpoint. The change of control rod reactivity leads to change in the reactor power and further adjusts the reactor outlet helium temperature. A PI controller is applied for the temperature control.

Fig. 2.6 Precooler/intercooler outlet temperature control system. As is shown in Fig. 2.6, the precooler outlet temperature control system and the intercooler outlet temperature control system have similar control logics. Both of them change the cooling water flow by adjusting the cooling water regulation valve opening to maintain the outlet temperature constant.

[FIGURE:2.7] Electric power control system

As shown in Fig. 2.7, the electric power control system changes the bypass flow by adjusting the opening of the bypass helium control valve to track the change of the electric power setpoint. During the steady-state operation, the bypass helium control valve is closed, and a P controller is selected for electric power control.

Fig. 2.8 Rotor speed control system. As is shown in Fig. 2.8, the speed control system has two controllers for filling and evacuating helium. The filling helium control changes the filling flow rate by adjusting the filling helium control valve, and the evacuating helium control changes the evacuating flow rate by adjusting the evacuating helium control valve. Both controllers use the PID controller.

[FIGURE:2.9] Gain scheduling control for GMR

Due to the high degree of nonlinearity of GMR, gain scheduling control was applied as shown in Fig. 2.9. Nonlinear control methods under gain scheduling were investigated [13]. Controllers at 5 different power levels were designed. Different controllers were combined with linear weight at varying load levels to achieve weighted control outputs, thereby addressing the issue of controller switching across different power levels.

The controller parameters obtained for each control system through frequency domain analysis are shown in Table 2.1. Among these, the electrical power control system employs a P controller, while the other control systems utilize PI controllers.

Table 2.1 The controller parameters at 100% FP. Reactor outlet temperature controller: 5×10^{-5} Rotor speed controller: 3.5×10^{-6} Precooler outlet temperature controller: 1.9×10^{-6} Intercooler outlet temperature controller: 3.1×10^{-6} Electric power controller: 2.4×10^{-10}

3 MRAC-based adaptive fault-tolerant control method

Since the GMR usually operates with few people on duty or unattended, the operator may not be able to respond in time after faults, fault-tolerant control is needed to reduce or suppress the impact. In view of the simple structure and easy use of PID control, it has been widely used in the industrial field. The working environment of the GMR is prone to causing faults and has high requirements for the reliability of the control method. Therefore, the adaptive fault-tolerant control should be applied to achieve a good control effect. In this study, an adaptive fault-tolerant control scheme based on MRAC is proposed.

3 MRAC Adaptive Fault-Tolerant Control Structure

The idea of MRAC control system structure is shown in Fig. 3.1. The main components of the MRAC control system structure diagram [16] assume the existence of:

$$\dot{x}_p = A_p x_p + B_p u$$

$$\dot{x}_m = A_m x_m + B_m r$$

$$u = K_r r + K_x x_p$$

$$e = x_p - x_m$$

$$\dot{e} = A_m e + (A_p + B_p K_x - A_m) x_p + (B_p K_r - B_m) r$$

A_m satisfied with Hurwitz stabilization, and for any given symmetric positive definite matrix Q, the symmetric positive definite matrix P can be found to satisfy the following Lyapunov equation:

$$A_m^T P + P A_m = -Q$$

Using P to construct a positive definite function $V(t)$:

$$V(t) = e^T P e + \operatorname{tr}\{(K_x - K_x^*)^T \Gamma_x^{-1} (K_x - K_x^*)\} + \operatorname{tr}\{(K_r - K_r^*)^T \Gamma_r^{-1} (K_r - K_r^*)\}$$

where Γ is an adjustable symmetric positive definite constant matrix; tr{} is the trace of the square matrix. Derivation of $V(t)$ can be obtained. When the terms are balanced, the model reference adaptive law can be obtained:

$$\dot{K}_x = -\Gamma_x B_p^T P e x_p^T$$

$$\dot{K}_r = -\Gamma_r B_p^T P e r^T$$

Since the system is asymptotically stable if and only if $e \to 0$, Q determines the convergence rate of the system.

4 Design of GMR Adaptive Fault-Tolerant Control System

In MRAC, an ideal system without external interference, its structure and internal parameters need to be determined in advance, so that the reference model can have the ideal output of the controlled object. However, due to various internal and external disturbances during the operation of the system, the actual output of the controlled object is not always consistent with the ideal output, so there will be an error $e(t)$ between the two. MRAC adaptive fault-tolerant control structure is shown in Fig. 4.1. From Fig. 4.1, the input of the reference model is the setpoint r, the output is y_P, and the deviation of y_P from the output y of the controlled object is e. The adjustable control parameter θ is obtained through the adaptive law so that the output y is close to the output y_P of the reference model [20].

$$\dot{\theta} = -\gamma e y_P$$

where γ is the learning rate. θ is not only related to the learning rate of adjustable parameters, but also related to the output and deviation of the reference model. Therefore, it is necessary to ensure that the reference model has high accuracy. The product of θ and the output of the PID controller is the output of the control system. Therefore, the output u of the adaptive fault-tolerant control system based on MRAC is obtained.

The steps of the MRAC adaptive fault-tolerant control structure diagram of GMR are:

1. According to the control objective, choose a suitable reference model whose output is the ideal output that the system wishes to achieve.
2. Define the control objective: the output of the controlled system should approximate the output of the reference model. Let the output error of the controlled system converge to zero in the control process.
3. Formulate the adaptive law: According to the error between the reference model and the controlled object, continuously adjust the controller parameters through the adaptive law, so that the system output continuously approaches the reference model. The reference model is the relationship between the setpoint and the measurement of each control system, which is obtained by identifying the change of the setpoint without fault condition. The adaptive law is designed by the MIT local parameter optimization method.

4.1 Rotor speed control system

For the speed control system, the control system adopts a coordinated control method based on signal switching and signal fusion to adjust the rotor speed and the helium pressure at the turbine inlet.

An adaptive fault-tolerant control system is designed for rotor speed and turbine inlet pressure, respectively, and jointly adjusts the filling and evacuating flow under the action of the two systems. The speed adaptive fault-tolerant control system based on MRAC is shown in Fig. 4.2.

The reference model is obtained by the method of system identification, and the reference transfer function model of the control system is obtained by ensuring that the output is consistent with the change of the setpoint. The reference model of the rotor speed describes the relationship between the setpoint and the measurement of the speed. The step change of the speed setpoint is carried out under the fault-free condition. The reference transfer function model of the rotor speed in the speed control system is:

The identified transfer function model is compared with the nonlinear model under step change and shown in Fig. 4.3.

[FIGURE:4.3] Rotor speed comparison

The reference model of turbine inlet pressure describes the relationship between the setpoint of turbine inlet pressure and the measurement. Under the fault-free condition, the setpoint of the turbine inlet pressure is changed stepwise. The reference transfer function model of the turbine inlet pressure in the speed control system is:

(4-5) and the output comparison between the identified transfer function model and the nonlinear model is shown in Fig. 4.4.

[FIGURE:4.4] Turbine inlet helium pressure comparison

It can be seen from Fig. 4.3 and Fig. 4.4 that the estimated value of the reference model of the speed control system after the setpoint changes is consistent with the actual output. The adaptive fault-tolerant control system is designed according to the reference model. After obtaining the reference model, a speed adaptive fault-tolerant control system based on MRAC is designed, and the learning rate γ is 5×10^{-14}.

4.2 Helium Temperature Control System

For the helium temperature control system, the control system adopts a coordinated control method based on the deviation between the actual outlet helium temperature and the output of the reference model to adjust the learning rate, and the learning rate to adjust PID parameters. The helium temperature adaptive fault-tolerant control system based on MRAC is shown in Fig. 4.5.

The reference model is obtained by the method of system identification. The reference model of the reactor outlet helium temperature control system describes the relationship between the setpoint and the measurement of the reactor outlet helium temperature. The step change of the reactor outlet helium temperature setpoint is carried out under the fault-free condition. The reference transfer function model of the reactor outlet helium temperature control system is:

(4-6) The identified transfer function model is compared with the nonlinear model under step change and shown in Fig. 4.6.

[FIGURE:4.6] Reactor outlet helium temperature comparison

It can be seen from Fig. 4.6 that the estimated value of the reference model of the reactor outlet helium temperature control system after the setpoint changes is consistent with the actual output. The adaptive fault-tolerant control system is designed according to the reference model. After obtaining the reference model, a reactor outlet helium temperature adaptive fault-tolerant control system based on MRAC is designed, and the learning rate γ is 1×10^{-5}.

4.3 The Precooler/Intercooler Outlet Helium Temperature Control System

For the precooler/intercooler outlet helium temperature control system, the control system adopts a coordinated control method based on the deviation between the actual precooler/intercooler outlet helium temperature and the output of the reference model to adjust the learning rate, and the learning rate to adjust PID parameters. The precooler/intercooler outlet helium temperature adaptive fault-tolerant control system based on MRAC is shown in Fig. 4.7.

The reference model is obtained by the method of system identification. The reference model of the precooler outlet helium temperature control system describes the relationship between the setpoint and the measurement of the precooler outlet helium temperature. The step change of the precooler outlet helium temperature setpoint is carried out under the fault-free condition. The reference transfer function model of the precooler outlet helium temperature control system is:

(4-7) The identified transfer function model is compared with the nonlinear model under step change and shown in Fig. 4.8.

[FIGURE:4.8] Precooler outlet helium temperature comparison

The reference model is obtained by the method of system identification. The reference model of the intercooler outlet helium temperature control system describes the relationship between the setpoint and the measurement of the intercooler outlet helium temperature. The step change of the intercooler outlet helium temperature setpoint is carried out under the fault-free condition. The reference transfer function model of the intercooler outlet helium temperature control system is:

(4-8) The identified transfer function model is compared with the nonlinear model under step change and shown in Fig. 4.9.

[FIGURE:4.9] Intercooler outlet helium temperature comparison

It can be seen from Fig. 4.8 and Fig. 4.9 that the estimated value of the reference model of the precooler/intercooler outlet helium temperature control system after the setpoint changes is consistent with the actual output. The adaptive fault-tolerant control system is designed according to the reference model. After obtaining the reference model, a precooler/intercooler outlet helium temperature adaptive fault-tolerant control system based on MRAC is designed, and the learning rate γ of both controllers is 0.01.

5 Control Performance Simulation Test

Three typical faults are selected: the reactivity disturbance fault, the precooler/intercooler loss flow fault and the main circuit helium leakage fault. The GMR simulation and verification platform is adopted for the fault-tolerant control performance simulation test.

5.1 Reactivity Disturbance Fault

With the GMR simulation platform, the GMR is operated at 100% FP, and the load setpoint is reduced to 90% FP stepwise at 500s. According to the simulation of Fig. 5.1, it can be seen that when a reactivity disturbance fault occurs, the reactor outlet helium temperature under MRAC control, the reactor power setting time is shortened by about 17.6%. The reactor outlet helium temperature setting time is shortened by about 67.9%. The turbine inlet helium pressure setting time is shortened by about 9.9%. The maximum deviation of rotor speed is reduced by 12.8%. The electric power setting time is reduced by about 48.8%, and the electric power overshoot is reduced by about 13.9%.

[TABLE:5.1] Indicators of the GMR system under reactive disturbance fault

5.2 Precooler/Intercooler Loss Flow Fault

At the same time, the flow rate of the precooler/intercooler is reduced to 40%. The simulation ended at 3000s. The simulation results are shown in Fig. 5.2. To compare the control performance, the results with traditional PID are also plotted.

[FIGURE:5.2] System responses with precooler/intercooler loss flow fault

The MRAC control system suppresses the precooler/intercooler temperature disturbance by adjusting the flow of subcooled water in the precooler/intercooler. The outlet temperature of the precooler/intercooler quickly returns to the setpoint.

Table 5.2 lists the performance indicators. Compared with the traditional PID control, under the MRAC control, the electric power setting time is reduced by about 48.8%, the electric power overshoot is reduced by about 13.9%, the rotor speed maximum deviation is reduced by 12.8%, the precooler outlet temperature setting time is reduced by 67.9%, the precooler outlet temperature maximum deviation is reduced by 10.46%, the intercooler outlet temperature setting time is reduced by 63.4%, and the intercooler outlet temperature maximum deviation is reduced by 10.46%.

5.3 The Main Circuit Helium Leakage Fault

With the GMR simulation platform, the GMR is operated at 100% FP, and the load setpoint is reduced to 90% FP stepwise at 500s. According to the simulation of Fig. 5.3, it can be seen that when the main circuit helium leakage fault occurs, the exhaust flow increases and the load drops stepwise. The electric power control system increases the bypass flow and the exhaust flow increases rapidly. The MRAC control system suppresses the parameter disturbance caused by helium leakage by adjusting the gas flow rate. Under MRAC control, the electric power setting time is shortened by about 43.3%. The electric power steady error is reduced by about 54.6%. The rotor speed steady error is reduced by about 52.6%. The rotor speed maximum deviation is reduced by 39.3%, and the turbine inlet helium pressure steady error is reduced by 59.7%.

[TABLE:5.3] Indicators of the GMR system under the main circuit helium leakage fault

The MRAC control of the GMR can achieve effective fault-tolerant control for three types of faults: reactivity disturbance fault, the precooler/intercooler loss flow fault and the main circuit helium leakage. The performance indicators have improved compared with traditional control.

6 Conclusion

The GMR system exhibits strong coupling characteristics and significant nonlinear behavior. To enable autonomous adaptation to complex and variable external environments and stringent load-following requirements, this paper proposes a fault-tolerant control method based on MRAC. The reference model was constructed through system identification, and the MIT adaptive law was adopted to achieve online adjustment of the controller output. The design allows the system, upon receiving fault diagnosis alerts, to switch to corresponding fault-tolerant control modes according to different fault types, effectively mitigating the impact of faults and ensuring continued safe and stable operation.

Simulation tests under three typical fault conditions led to the following conclusions:

1. An adaptive fault-tolerant control method based on MRAC is proposed for the gas-cooled microreactor.

2. The model reference adaptive control systems are designed and controller parameters are derived.
3. Compared with the traditional PID control method, the MRAC control system shows significant improvements in response time, overshoot, and steady-state error across all fault scenarios, demonstrating its effectiveness for fault-tolerant control of GMR systems.

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