Research and Application of Adaptation Technology for Steam Generator Water Level Control Mechanism in Nuclear Power Units

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Abstract

Under high-load operating conditions in nuclear power units, the feedwater pump speed control system and the main/bypass valve control system become coupled, leading to regulatory oscillations in the control system, which poses challenges to the reliability and durability of actuators and also impacts the safe and stable operation of nuclear power units. Therefore, solving the problem of control system coupling oscillations under high-load conditions is of paramount importance. Through in-depth analysis of fluctuation curves from multiple sites, it was found that the slow response characteristics of actuators, which cannot timely follow the response speed of the control system, constitute the primary cause of regulatory fluctuations. By evaluating actuator response characteristic curves, optimizing valve actuator parameters, and implementing matched settings for proportional gain, velocity gain, and minimum loop gain, optimization of response characteristics is achieved in three aspects: good small-signal tracking, low large-signal overshoot, and fast time response characteristics, thereby enhancing the actuator’ s good response and control characteristics under both small-signal and large-signal conditions. From the perspective of actuator regulation characteristics, the stability of evaporator water level control under high-load conditions is improved.

Full Text

Research and Application of Adaptation Technology for Steam Generator Level Control Actuator in Nuclear Power Units

Abstract

Under high-load conditions, coupling between the feedwater pump speed regulation system and the main/bypass valve regulation system in nuclear power units induces control system oscillations, challenging actuator reliability and durability while compromising safe and stable unit operation. Resolving this coupling-induced oscillation is therefore critical. In-depth analysis of fluctuation curves from multiple plant sites reveals that the primary cause of regulation fluctuations lies in the actuator' s slow response characteristics, which prevent timely tracking of control system commands. By evaluating actuator response characteristic curves and optimizing valve actuator parameters through coordinated settings of proportional gain, speed gain, and minimum loop gain, this work achieves comprehensive response optimization: improved small-signal tracking, reduced large-signal overshoot, and enhanced time-response characteristics. This optimization enhances actuator performance across both small and large signal regimes, thereby significantly improving steam generator level control stability under high-load conditions from the perspective of actuator regulation characteristics.

Keywords: Steam generator level control; Regulation coupling; Response characteristics; Actuator adaptation

1. Introduction

Steam generator level control systems perform critical process control functions in nuclear power plants, primarily maintaining the secondary side water level at its setpoint [1]. Excessively high water levels increase steam moisture content at the outlet, accelerating turbine erosion and impacting unit lifespan or even causing damage. Conversely, excessively low levels can expose U-tube tops, potentially inducing water hammer in feedwater lines and damaging the steam generator, posing severe safety threats. The steam generator level control logic is complex with numerous control variables; the design margin between normal operating values and protection actuation setpoints is narrow, while false water level effects from process systems [2] are significant. These factors make steam generator level control one of the most critical and sensitive systems in nuclear power units. Statistics show that over 50 reactor automatic trips have occurred domestically and internationally due to steam generator level control anomalies, making it the primary cause of unit transients or automatic reactor trips. Therefore, level control stability is crucial for safe and stable nuclear power unit operation.

Multi-site nuclear power units exhibit varying degrees of level regulation fluctuation anomalies under different operating conditions, particularly at high loads, which in severe cases trigger deviation alarms and require manual operator intervention, creating potential threats to safe and stable operation. To improve control performance, researchers have investigated numerous approaches, including modified controllers [3-5], dual PI control [6], active disturbance rejection control [7], fuzzy control [8], and neural network control [9]. While these methods have achieved certain results in steam generator level control, their effectiveness in mitigating regulation oscillation has been limited. Consequently, enhancing and improving steam generator level control system stability under high-load conditions is particularly critical and urgent [10].

2.1. Principle Description

Nuclear power unit steam generator level control primarily consists of the main feedwater valve regulation system and the feed pump speed regulation system, as shown in Figure 1 [Figure 1: see original paper].

The main feedwater valve regulation system controls level by adjusting feedwater flow into the steam generator. Each steam generator' s normal feedwater circuit includes two parallel lines: the main feedwater valve on the main line handles level regulation during high-load operation, while the bypass valve on the bypass line serves low-load and start-up/shutdown conditions. The main feedwater valve uses the difference between steam flow at the generator outlet and feedwater flow at the inlet (the steam-water deviation signal) as a feedforward signal in the open-loop channel, while the difference between measured water level and setpoint (the level deviation signal) passes through a PID (proportional-integral-derivative) control element to generate a closed-loop control signal. These two signals then pass through a PI (proportional-integral) control element to output the main feedwater valve position signal [11-12].

The bypass valve uses the sum of the deviation adjustment between level setpoint and measured value plus a total steam flow feedforward signal as its position signal [13], remaining fully open during full-power operation without participating in regulation. The feed pump speed regulation system adjusts the scoop tube position to control speed based on control signals, maintaining the pressure difference between the steam generator feedwater header and steam header equal to a load-dependent setpoint. This maintains an approximately constant pressure differential across the feedwater flow control valves, eliminating coupling effects among the three steam generators and meeting water supply requirements. The three steam generators share a common feedwater header; changing one generator' s feedwater valve position to adjust flow when its level [14] deviates from setpoint alters the feedwater header pressure.

2.2. Analysis of Regulation Oscillation Causes

Periodic fluctuations commonly occur in nuclear power unit steam generator main feedwater valves, as shown in Figure 2 [Figure 2: see original paper]. Steam generator feedwater flow fluctuations cause feedwater valve position changes, which alter the steam-water pressure difference, triggering feed pump speed adjustments. Feed pump speed regulation changes feedwater flow, and steam-water flow deviations cause feedwater valve position changes. This coupling between the feed pump speed regulation system and the main/bypass valve regulation system induces control system oscillations, challenging actuator reliability and durability while threatening safe and stable unit operation.

Based on in-depth analysis from multiple nuclear power plant sites, the fundamental cause of periodic fluctuations in steam generator main feedwater valves is the mutual coupling between the main feedwater valve regulation system and the feed pump speed regulation system. The primary reason for this coupling is that the regulation characteristic time of the main feedwater valve is similar to that of the feed pump speed regulation system [15]. Two direct factors produce regulation resonance in correlated control systems: the frequency characteristics ϕ of the control systems. When two control systems have identical or similar frequency characteristics, they produce constant-amplitude oscillations—the foundation of regulation resonance. The amplitude of these constant-amplitude oscillations directly correlates with phase difference. Frequency characteristic calculations include not only regulator time characteristics but also actuator response time.

Therefore, the primary measure to resolve main feedwater valve fluctuations is to break the coupling between the main feedwater valve regulation system and the feed pump speed regulation system. By evaluating actuator response characteristic curves and optimizing steam generator level actuator regulation characteristics, this approach improves high-load steam generator level control stability from the actuator regulation characteristic perspective.

3. Research on Adaptation Technology Based on Actuator Response Characteristics

To eliminate abnormal fluctuations in main feedwater valves, this study investigates adaptation technology based on actuator response characteristics. Steam generator level control actuators employ pneumatic control valves [16-18]. The research approach focuses on three aspects: small-signal tracking setting, large-signal overshoot setting, and full-stroke time response characteristic setting, as shown in Figure 3 [Figure 3: see original paper]. The primary objective is achieving comprehensive response optimization: good small-signal tracking, low large-signal overshoot, and fast time response characteristics, thereby enhancing actuator performance across both small and large signal regimes.

3.1. Small-Signal Tracking Setting

Small-signal tracking setting involves applying small step changes to the main feedwater valve command signal and observing the actual valve response. As shown in Figures 4 [Figure 4: see original paper] through 6 [Figure 6: see original paper] (under different parameter settings), actuator response curves are obtained for step changes of 1%, 2%, 3%, and 4%. Small-signal tracking setting must satisfy two indicators: first, the actual valve opening change under small-signal variations; second, the tracking coefficient of valve opening change under small-signal variations: $\Delta \geq$. Here, represents the actual valve opening change under command signal , is the tracking coefficient, is the time required for the actual opening to reach 63.2% of the command signal, and is the standard small-signal time response value.

Small-signal tracking setting must meet these indicator requirements. If not satisfied, proportional gain, speed gain, and minimum loop gain are adjusted through matching settings to achieve compliance.

3.2. Large-Signal Overshoot Setting

Large-signal overshoot setting involves applying a 25% step change to the main feedwater valve command signal and observing the actual valve response under large-signal variations. As shown in Figures 7 [Figure 7: see original paper] through 9 [Figure 9: see original paper] (under different parameter settings), actuator response curves are obtained for step changes of 0%, 25%, 50%, 75%, and 100%. Large-signal overshoot setting must satisfy two indicators: first, the overshoot amount under large-signal variations must be less than the standard overshoot rate value; second, the valve opening change speed under large-signal variations: $\Delta \leq$. Here, represents the overshoot amount under command signal , is the standard overshoot rate value, is the time required for the actual opening to reach 63.2% of the command signal, and is the standard large-signal time response value.

Large-signal overshoot setting must meet these indicator requirements. If not satisfied, proportional gain, speed gain, and minimum loop gain are adjusted through matching settings to achieve compliance.

3.3. Full-Stroke Time Response Characteristic Setting

Full-stroke time response characteristic setting verifies that the main feedwater valve' s full-stroke opening and closing times meet process system requirements. As shown in Figure 10 [Figure 10: see original paper], the objective is accelerating actuator full-stroke response speed—verifying that when the main feedwater valve command signals are fully open and fully closed, the actual full open and full close times satisfy the following requirements: and , where is the standard full-stroke opening time value and is the standard full-stroke closing time value.

If full-stroke time response characteristics cannot meet requirements, adjustments are made through three aspects: actuator characteristic parameter optimization, air supply pressure range adjustment, and flow amplifier regulation to achieve compliance with standard values.

4. Engineering Application and Verification

Through small-signal tracking setting, large-signal overshoot setting, and full-stroke time response characteristic setting, the adaptation technology based on actuator response characteristics achieves comprehensive optimization: good small-signal tracking, low large-signal overshoot, and fast time response, thereby enhancing actuator performance across both small and large signal regimes.

This adaptation technology has been implemented at multiple domestic nuclear power plant sites. Taking one domestic nuclear power base as an example, Figure 11 [Figure 11: see original paper] compares steam generator level control response curves under high-load conditions before and after improvement. Before improvement, main valve regulation fluctuation ranged from 5-8%; after improvement, it reduced to 1-3%, representing a substantial improvement with fluctuation amplitude decreasing to 10-40% of its original value, significantly enhancing steam generator level control stability.

5. Conclusion

High-load conditions in nuclear power units cause coupling between the feed pump speed regulation system and the main/bypass valve regulation system, resulting in steam generator level control system oscillations. The primary cause of this coupling is the similar regulation characteristic times between the main feedwater valve and the feed pump speed regulation system. This paper proposes an adaptation technology based on actuator response characteristics that, through small-signal tracking setting, large-signal overshoot setting, and full-stroke time response characteristic setting, enhances actuator performance across both small and large signal regimes. Implemented at multiple domestic nuclear power plant sites, this technology substantially reduces fluctuation amplitude and ensures safe and stable unit operation.

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Note: Figure translations are in progress. See original paper for figures.