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Control Algorithm Improvement for Reactor Makeup Water and Boric Acid Makeup Flow Control Loops

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1. Introduction

The Reactor Coolant Makeup subsystem, part of the Chemical and Volume Control system (CVCS), consists of two circuits for adding Reactor Makeup Water and Boric Acid into the Reactor Coolant System (RCS), to control the boron concentration and maintain the required water volume in the RCS. Each of these two circuits have a flow control loop - Reactor Makeup Water Flow Control, and Boric Acid Makeup Flow Control Loop. The flow control loops inject a predefined quantity of water and boric acid into the RCS. The flow control for each of the two loops is realized with a flow control valve whose operability is determined by a pilot solenoid valve's status.

Depending on the operation mode, whether the related pump for supplying the corresponding flow rate operates or not is determined. A rapid increase in the related flow rate during transient state due to operation mode change to start batching process has been frequently observed in operating nuclear power plants. As a result, it can cause a large amount of reactor makeup water or boric acid to be unintentionally supplied. Accordingly, this can make it difficult to control the boric acid concentration. To mitigate the overshoot in the process variable, we proposed an improved control algorithm and performed dynamic simulations to confirm the effectiveness of this solution.

2. Background for Improved Control System

In this section, basic functions and principles of the flow control loops for reactor coolant makeup subsystems and potential problems are described.

2.1 System Description

Each control valve is manipulated according to the corresponding Proportional-Integrative-Derivative (PID) controller's output in the closed-loop reactor coolant makeup control system based on the feedback control scheme. During batching process mode in which the system is activated with the related pump operating, a pilot solenoid valve is energized to allow instrument air to modulate the control valve. In this case, the setpoint value as a desired flow rate for automatic control in each controller has to be allocated by the operator to keep the level in the Volume Control Tank (VCT) and ensure the correct boric acid concentration is achieved in the RCS. Through the automatic process of supplying an appropriate amount of reactor makeup water and boric acid into the RCS, the operator can monitor the consequential changes in nuclear reactivity due to the varying boric acid concentration.

The system continuously integrates the flow rate over time during batch mode to calculate the supplied total quantity. If this integrated flow is greater than the predefined batch quantity entered by the operator, the batching process will terminate. Consequently, the flow control valve will be forced to be closed according to the fail-safe position as the pilot solenoid valve is de-energized until a new batch process starts.

2.2 Potential Problem

If the batching process is not required, an error signal which is the input of the PID controller will be maintained to be a positive value as the measured flow rate is close to zero due to the closed control valve while the desired setpoint for flow is a certain positive value entered by the operator. For this reason, the PID controller's output value for the control valve position demand will be eventually saturated to 100%, which is attributed to the constant 'HOLIM(High Output Limit)', by the anti-windup function as the PID controller is kept in automatic mode [1].

Immediately after the operation mode is changed to start a new batching process, the control valve can be rapidly opened to an almost full open position since the controller was already requesting 100% as a valve position demand output. It can cause a big fluctuation in the flow rate. The control system will try to automatically compensate this overshoot using the PID controller based on the negative feedback control scheme. However, a considerable amount of water or boric acid can be supplied more than expected, since it will take a long time until the flow control loop reaches a steady state. In addition, an alarm can be triggered by high flow deviation signal, which is generated if the deviation between the measured flow and the desired flow exceeds a predefined threshold value.

In order to prevent this scenario in the nuclear power plant, it is required that the operator should manually adjust the PID controller's output to 0% prior to start batching process. Through this operator's manual procedure, the fast change in the flow due to the mode conversion can be avoided. However, it imposes the extra human burden on the operator to perform additional steps.

3. Proposed Algorithm

The existing flow control system was implemented to apply a simple automatic control loop algorithm regardless of the batching process mode. The PID controller does not track the actual position of the control valve due to the de-energized pilot solenoid valve's status when the batch is not required. This is the main reason for the considerable overshoot in the resulting flow rate during the transient state after the batching process starts. To improve the dynamic response, it should be considered that the characteristic of the process in the flow control loop is different depending on the selected operation mode. Accordingly, the control algorithm proposed in this paper reflects this relationship by adding the status for operation mode as an input signal as shown in Fig. 1. The part of the block diagram added for improving control algorithm is shown in red color.

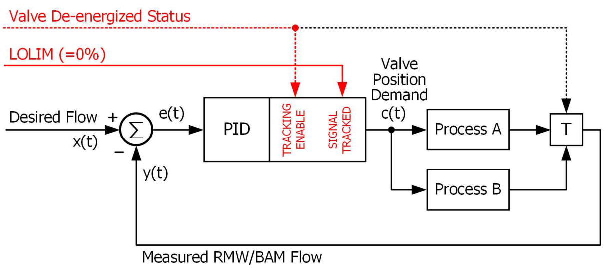

Fig. 1. Proposed control algorithm in RMW/BAM flow control loop

During the valve de-energized status in which the batching process is not performed, the control valve is maintained to be closed. For the bumpless transfer in case of mode change, the position demand signal for the control valve, which is the PID controller's output, should be matched with the actual valve position. For this purpose, the output tracking function is added in the original control algorithm. According to the proposed algorithm, the constant 'LOLIM(Low Output Limit)', whose nominal value equals to zero, has to be tracked by the PID controller before starting the batching process.

In the batching process mode, the pilot solenoid valve for the respective flow control loop (Reactor Makeup Water or Boric Acid) will be energized and the related pump will operate. For this reason, the corresponding process model, which is denoted by 'Process A', should be taken into account. In this case, the controller's output will be updated at each cycle time based on calculation of the PID controller, since the tracking function is disabled. When the batch is complete, the operation mode will be the valve de-energized status, for which the process model corresponds to 'Process B' in Fig. 1.

4. Simulation Results

To verify the effectiveness of the proposed control algorithm, we performed the dynamic simulation. It is necessary to observe the related results in the flow control loops for the current system and the proposed system due to the operation mode change from the valve de-energized status to the batching process mode. The transfer functions for the PID controller and the process models for both cases and their internal parameters were assumed as shown in Table I. In addition, the unit cycle time in the controller for the discrete time based calculation was assumed to be 0.1 seconds. The controller's output should be limited according to the predefined range that is LOLIM ≤ c(t) ≤ HOLIM.

Table I: Assumption for simulation

● PID controller
$\mathrm{C(s)} = K\left(1 + \frac{1}{\tau s}\right) \cdot E(s)$
$K = 1.69, \tau = 5.0$ sec .
HOLIM = 100.0%
LOLIM = 0 %
● Process Model
$\mathrm{Y(s)} = \left(\frac{l e^{-\theta s}}{\sigma s + 1}\right) \cdot C(s)$
$l = \begin{cases} 1.6 & \text{for Process A} \\ 0.01 & \text{for Process B} \end{cases}$
$\sigma = 4.5$ sec ., $\theta = 1.5$ sec .

Fig. 2 shows the simulation results for the process variables and the controller's output in the flow control loops. It was assumed that each flow control system was inactive for 10 seconds. As the instrument air for opening the control valve is not allowed due to the de-energized pilot solenoid valve, each of the measured flow rate y(t) for the current system and the proposed system is close to zero while the desired flow rate x(t) is maintained to be 50%. In the proposed system, the PID output c(t) is fixed to the LOLIM (=0%) which corresponds to the actual valve position by the enabled tracking function before starting the batching process. On the other hand, the controller's output in the current system is shown to be 100% requiring full opening of the control valve.

After the batching process starts at 10 seconds, the automatic feedback control is performed with the different initial conditions for both systems. In the current system, a big fluctuation in the flow rate is discovered due to the stabilizing process from 100% of controller's output. Since the measured flow y(t) exceeds the setpoint x(t) by more than a certain threshold value that is assumed to be 20% for simplicity in this paper, it can cause the flow deviation alarm and can stop the automatic batching process for supplying the reactor makeup water or the boric acid. In the proposed system, it is shown that the transient response is considerably improved without any overshoot in the flow rate. These simulation results confirmed that the proposed control system satisfies the acceptance criteria that the flow control loop should not cause any alarms and should not generate any interlock signals to stop automatic batching process in all operating modes.

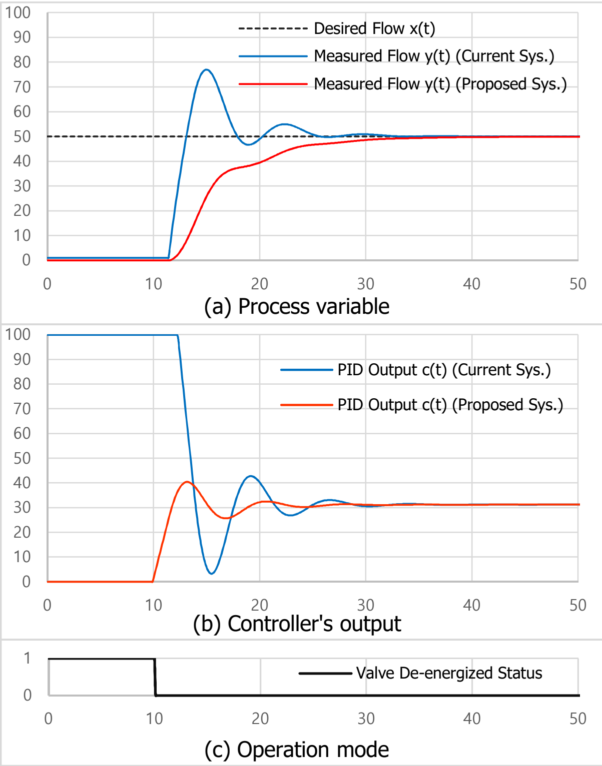

Fig. 2. Simulation results for dynamic response

5. Conclusions

In this paper, we proposed a control algorithm in the RMW or BAM flow control loops for improving the transient response in the event of operation mode change. If this control algorithm is applied in the current system, it is not required for the operator to perform a series of manual procedures to prevent a big overshoot in the flow rate without tripping the batching system or triggering any alarms for starting the batching process. In addition, it is expected that the operation mode can be changed smoothly through the proposed algorithm.

REFERENCES

[1] Y Peng, D Vrancic and R Hanus, "Anti-Windup, Bumpless, and Conditioned Transfer Techniques for PID Controllers," IEEE Control Systems, 16.4 (1996): 48-57.