On study of steam bypass and pressure control system for Lungmen nuclear power plant

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Abstract

The investigation of steam bypass and pressure control system (SBPCS) is performed by RETRAN-3D code for Lungmen nuclear power plant. The purposes of this study are: 1) to demonstrate that the dynamic response of SBPCS is capable of controlling the system pressure smoothly when the reactor steam generation exceeds the steam flow used by the turbine, and 2) to study the effect of pressure regulator (PR) on dynamic response. The dynamic response of SBPCS is evaluated by means of the perturbations induced by pressure setpoint changes. The parametric study of SBPCS performs the effect of lead-lag regulator on the dynamic response. Finally, the resultant dynamic responses indicate that the design of SBPCS is capable of damping the system oscillation and bring the system to a stable state.

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Keywords: SBPCS; pressure control; Lungmen; ABWR.

1. Introduction

The Lungmen nuclear power plant (LMNPP), which has two Advanced Boiling Water Reactors (ABWRs), is the fourth nuclear power plant in Taiwan. The specific design of steam bypass system

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controlled by steam bypass and pressure control system (SBPCS) provides 110% bypass capacity [1], more than the typical value in the order of 35% for most plants [2]. This specific design feature can withstand a transient caused by turbine trip (TT) or load rejection (LR) from rated power without scram. Another issue associated with SBPCS is the pressure regulator (PR), consisting of lead-lag controller that controls the turbine control valves (TCVs) during normal operation. The PR is required to control the system pressure smoothly when the reactor steam generation exceeds the steam flow used by the turbine, satisfied with the criteria specified in startup test procedure documents [3].

During the past, the RETRAN-02 code was one of the major tools for thermal-hydraulic analyses of nuclear reactors in Taiwan [4,5,6]. The code version of RETRAN-3D is adopted now for the following associated analyses. The construction of Lungmen RETRAN-3D system model was based on the previous Lungmen RETRAN-02 system model which has been employed for several studies and analyses [7, 8]. Additionally, the SBPCS model was constructed and incorporated into the Lungmen RETRAN-3D system model, representing the coupling effect between thermal-hydraulics and neutron kinetics. By means of Lungmen RETRAN-3D system model and embedded SBPCS model, the following two simulations are performed: 1) to demonstrate that the dynamic response of SBPCS is capable of controlling the system pressure smoothly, and 2) to study the effect of PR on dynamic response. The analysis results thus could be applied furthermore to support the Lungment startup tests.

### Nomenclature

| Symbol | Description |
|--------|-------------|
| K      | gain        |
| $\tau_{\text{Lead}}$ | lead time constant |
| $\tau_{\text{Lag}}$ | lag time constant |

#### 2. Modeling

##### 2.1 Lungmen system model

Compared with previous Lungmen RETRAN-02 system model [7,8], Lungmen RETRAN-3D system model incorporates three updated control system models, including SBPCS, recirculation flow control system (RFCS), and feedwater control system (FCS). The updated Lungmen RETRAN-3D system is planned on transient safety evaluation, startup test prediction, and other general purposes for LMNPP. Fig. 1 represents the nodalization of Lungmen RETRAN-3D system model. The nuclear steam supply system (NSSS) including 1 reactor pressure vessel (RPV), 1 lumped main steam line, feedwater injection, related controls, and safety systems, is simulated in the model. The system nodalization contains 91 control volumes, 120 junctions and 50 heat conductors. The reactor core in the RPV is modelled as two parallel flow channels, each with 25 nodes simulating the active core and bypass regions, respectively. Heat generation conducted from fuels is modelled with 25 heat conductors, while heat transfer of the channel box is simulated with another 25 heat conductors. The LMNPP RPV has 10 recirculation internal pumps (RIPs) classified into three groups, 3 RIPs for each of the first and second groups, and 4 RIPs for the third group. The RIPs in group 3 are connected to the motor generator (M/G) set; they are tripped by turbine stop or control valves closure signals when insufficient bypass valve opening is detected, or a high vessel dome pressure signal or low vessel water level signal is initiated. The other 6 RIPs are not connected to the M/G set, thus, the trip signal for group 2 RIPs is initiated by low vessel water level L2 signal, and group 1 RIPs is also tripped with L2 signal, but has 6-sec delay. Four turbine control valves (TCVs) and 1
equivalent turbine bypass valve (TBV) are modelled by fill junctions. The steam mass flow rates pass through TCVs and TBV are controlled by SPBCS built in Lungmen RETRAN model.

2.2 Modeling of SBPCS

The design of SBPCS design is a triplicate digital control system including PR, load demand adjustor, and steam bypass controller. SBPCS provides direct signal, i.e., turbine steam flow demand signal, to control the positions of TCVs during normal operation. Fig. 2 represents the equivalent SBPCS control block diagram built in Lungmen RETRAN-3D system model. The difference of pressure setpoint and sensed dome pressure is submitted to PR, calculating the load demands which are transformed to equivalent steam flow rates based on the demand-steam flow curves (Fig. 3). During LL and TT transients, the PR controls bypass valves (BPVs) to vent steam flow to condenser. The steamline compensator represented in Fig. 2 is not credit in current Lungmen SBPCS design. Therefore, the signal is bypassed by setting the numerator in steamline compensator zero. (1) represents the transfer function of PR, consisting of a PR gain, two lead compensators, and three lag compensators. The lead compensator, \((τ_{\text{Lead,1}}S+1)\), and lag compensator, \((τ_{\text{Lag,1}}S+1)\), are utilized to stabilize the dome pressure control and responses. The lag time constant, \(τ_{\text{Lag,3}}\), is designed to attenuate the pressure error. The vendor recommended that it is no necessary to change \(τ_{\text{Lead,1}}\), \(τ_{\text{Lag,1}}\), and \(τ_{\text{Lag,3}}\). However, the time constants, \(τ_{\text{Lead,2}}\) and \(τ_{\text{Lag,2}}\), are possible to be adjusted for the improvement of SBPC closed-loop control response. The following parametric study will focus on the time constants, \(τ_{\text{Lead,2}}\) and \(τ_{\text{Lag,2}}\).

\[
G_{\text{PR}}(S) = \frac{K(τ_{\text{Lead,1}}S + 1)(τ_{\text{Lead,2}}S + 1)}{(τ_{\text{Lag,1}}S + 1)(τ_{\text{Lag,2}}S + 1)(τ_{\text{Lag,3}}S + 1)}
\]  

(1)

Table 1. The lead-lag time constants

| No. | Lag time constant (s) | Lead time constant (s) |
|-----|-----------------------|------------------------|
| 1   | 2                     | 0.4, 0.8, 1.2, 1.6     |
| 2   | 4                     | 0.8, 1.6, 2.4, 3.2     |
| 3   | 6                     | 1.2, 2.4, 3.6, 4.8     |
| 4   | 8                     | 1.6, 3.2, 4.8, 6.4     |
3. Analysis of time domain response and parametric study

The time domain response is induced by a step change of pressure setpoint while the Recirculation Flow Control System (RFCS) is in manual or auto control modes. According to the Lungmen startup test procedure [3], the PR setpoint is decreased and then increased rapidly by steps up to 69 kPa. The size of step change is limited by 25 kPa in first test, followed by a 45 kPa step change, and ending with a 69 kPa step change. This cautious method ensures that the system is not divergent or marginally stable. Additionally, according to the previous study [7], the RFCS auto mode can mitigate the transient
oscillation further than the RFCS manual mode. Therefore, the maximum step change of 69 kPa and RFCS manual mode are utilized for the following analyses, bounding all step changes of pressure setpoint as well as oscillation amplitudes.

This perturbation is performed at an initial power/core flow condition of 100%/100% of rated value. Different lead-lag time constants listed in Table 1 are adopted to determine the effect of $\tau_{Lag,2}$ and $\tau_{Lead,2}$ on time domain response. Fig. 4 represents the time domain response with the application of different lead-lag time constant, showing that all combinations of lead-lag time constants are satisfied with the acceptance criteria specified in Lungmen startup test procedure. Fig. 5 shows the trend of overshooting and the trend of time from the start of step change to overshooting via different lead-lag time constants. It also means that an optimization may exist within the lag time constant of 4 to 6 s with the lead time constant of 50 % to 70 % of lag time constant. Finally, the resultant dynamic responses indicate that the design of SBPCS is capable of damping the system oscillation and bring the system to a stable state.

**Fig. 5 The effect of lead-lag time constants (a) overshooting; (b) time to peak overshooting**

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