Journal of the Korean Nuclear Society
Volume 26, Number 3, September 1994

A Study on Improvement of PWR Steam Generator Water Level Control at Low Power Operation

Jae-Hee Yun and Jai-Bok Han
Korea Atomic Energy Research Institute
Joon Lyou
Chungnam National University
(Received March 17, 1994)

저출력시 원전 증기발생기 수위제어 개선 연구

윤재희 · 한재복
한국원자력연구소
유 준
충남대학교
(1994. 3. 17 접수)

Abstract

This paper presents an improved water level control scheme for Pressurized Water Reactor(PWR) Steam Generator(S/G) at the low power operation and transient states. To reduce fluctuations of the water level by the swell and shrink phenomena, the scheme adds feedforward terms considering S/G pressure and the feedwater temperature into the conventional proportional-integral feedback controller. The simulation results using the Compact Nuclear Simulator show that smaller level errors and much faster settling time than those of the conventional scheme can be obtained. The proposed algorithm is easily implementable and has a potential for the real applications.

요 약

가압경수로형 원자력발전소의 저출력 및 과도상태에서의 개선된 증기발생기 수위 제어 방식을 제시하였다. 수축 및 팽창 현상에 의한 수위의 요동을 줄이기 위해 기존의 비례 · 적분 제어기에 증기발생기 압력 및 급수온도를 고려한 앞먹임 보상부를 첨가하였다. 원전 훈련용 시뮬레이터를 이용하여 시뮬레이션을 수행한 결과 기존방식에 비해 적은 수위오차, 훨씬 빠른 진정시간을 얻을 수 있었다. 제시된 알고리즘은 구현이 용이하고 실제 적용도 가능하리라 판단된다.

1. Introduction

The Steam Generator (S/G) is a very important facility in the Nuclear Power Plant(NPP) which determines the plant responses when some changes in the operating loads occur. S/G is the vertical U-tube heat exchanger which operates with the reactor coolant on the primary side and the feedwater in the secondary side. S/G water level control is to maintain the water level within the prespecified limits by regulating the feedwater flow to S/G. In case that the water level is too low, the reactor will be tripped automatically by Plant Protection System(PPS) to protect fuel damages, while when the water level is too high, the turbine will be tripped due to too much moisture carryover to the turbine[1]. Therefore, to maintain S/G water level at its setpoint is important in overall plant availability and safety aspects.

Unfortunately, due to the presence of steam bubbles in the tube bundle region, S/G water level is known to temporarily respond in the adverse manner to input variations: the level first appears to increase under an augmented steam flow and to drop under an increased feedwater flow. These effects, respectively known as swell and shrink phenomena, are dominant at the low power operation, especially in the plant startup and transients rendering more hazardous the use of high control loop gain. Hence, particular attention should be paid to the controller design at the low power (typically less than 20% of full power) so as to reduce fluctuations of the water level while keeping a sufficient margin[2, 3].

In this paper, we analyze the factors which cause the swell and shrink of S/G water level and propose an improved control algorithm which includes feedforward terms considering S/G pressure and the feedwater temperature into the conventional Proportional and Integral(PI) feedback part. To verify the performance of the proposed control algorithm, the Compact Nuclear Simulator(CNS) being operated at Korea Atomic Energy Research Institute(KAERI)[4] has been used.

2. Swell and Shrink Phenomena

The figure 1 shows the conventional S/G water level control system.

It is basically a three-element control scheme using S/G water level, the steam flow, and the feedwater flow as its inputs. During the low power operation,

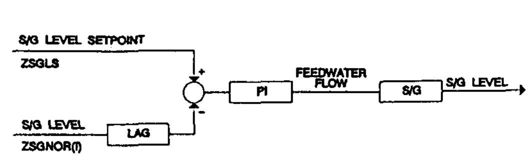

Fig. 1. Conventional Steam Generator Water Level Control System at Low Power

since fluid flow measurements are very inaccurate, the scheme uses only the water level as its input. To make the level control at the low power more difficult is that the measured level is temporarily opposite to the expected one as swell and shrink become dominant. In order to improve the control performance at the low power, it is necessary first to investigate the fundamental factors which cause swell and shrink, and then to reflect these into the controller design.

The main factor is changes of S/G pressure. When the steam flowrate is varied through the turbine admission valve or the bypass valve, S/G pressure changes inversely because S/G is a saturated process. When the steam flow is increased (power is increased), the steam pressure decreases and the two phase fluid in the riser region expands leading to the measured water level up. This phenomena is called "Swell". Upon observing the increased water level, S/G water level controller reduces the feedwater flow demand, although the actual water level should be decreasing. This reverse control action induces many reactor trips in the real plants. On the other hand, if the steam flowrate decreases (power decreases) by a reduction of the turbine loads, the amount of steam consumption would be less than that of steam generation. This unbalance in the steam quantity makes S/G pressure rise, which in turn causes a rapid collapse of steam bubbles existing in the water-steam mixture of the tube bundle region. Since the volume taken by the water-steam mixture suddenly decreases with the collapse of steam bubbles, water mass from the downcomer moves into the empty region leading to the indicated water level down. This phenomenon is called "Shrink". In reaction to shrink, S/G water level controller increases the feedwater flow demand, although the actual water level should be increased.

The second major factor is the incoming cold feedwater into S/G. When the feedwater flowrate is increased, the cold feedwater results in condensing the water-steam mixture in the lower part of the tube bundle region. As a result, suction occurring there produces increased flow in the downcomer leading to a drop of the water level.

This phenomenon called shrink is dominant at the low power, because the feedwater is much colder comparing to the temperature at the high power. The counter phenomenon called swell occurs when the feedwater flowrate decreases.

3. Proposed Improved Control Algorithm

It was pointed out that S/G water level is difficult to control at the low power due to the swell and shrink, and that two major causes of swell and shrink are S/G pressure changes and the cold feedwater entering into S/G secondary side. In this section, we present an improved water level control algorithm which can explicitely account for the swell and shrink.

The figure 2 shows the devised algorithm using S/G pressure and feedwater temperature signals as the additional controller inputs.

3.1. Consideration of Feedwater Temperature

The feedwater temperature varies by maximum 200°C depending on the reactor power. In the low power case, the difference between feedwater and reactor coolant temperatures is approximately 200°C. This large difference causes the water level to be shrunk when the feedwater flowrate is increased. In addition to the shrink and swell (swell is minor comparing to shrink), S/G water level response is delayed about 2~3 minutes due to internal flow circulations. These effects complicate the water level control.

The figure 3 shows a variable gain profile with respect to the feedwater temperature.

The profile was derived based on the startup data from the simulator at KAERI, which is modeled for GORI units 3 and 4. To compensate for the effects on the water level by low feedwater temperatures, this gain profile is implemented as the feedforward term in Figure 2.

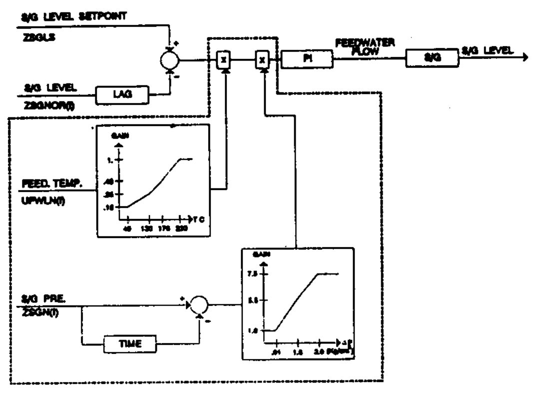

Fig. 2. Improved Steam Generator Water Level Control System at Low Power

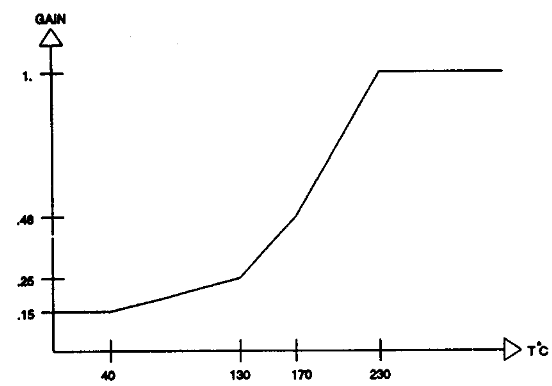

Fig. 3. Variable Gain for Feedwater Temperature

3.2. Consideration of S/G Pressure Changes

S/G pressure signal is an effective index regarding the occurrence of swell and shrink phenomena. Other indexes such as the difference between feedwater and steam flows, changes of steam flow may be used, but are not practical in the sense that fluid flow measurements accompany too much errors. S/G pressure changes ΔP at the time t can be calculated by

$$\Delta P(t) = P(t) - P(t-\tau) \qquad (1)$$

where P(t) is the current measured value, and $P(t-\tau)$ is the stored value before seconds.

The figure 4 contains a variable gain profile with respect to S/G pressure changes.

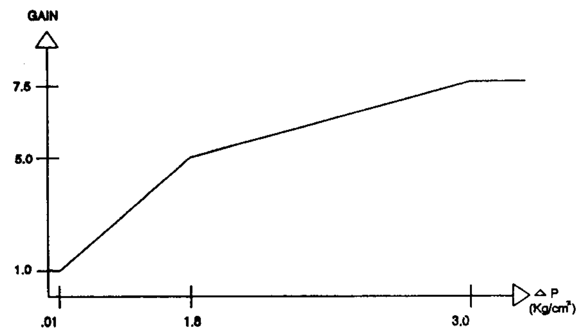

Fig. 4. Variable Gain for Steam Generator Pressure

S/G pressure typically varies from 77 to 65Kg cm^2 depending on the reactor power. The profile was obtained based on the water level versus ΔP curves from the simulator. To compensate for the water level fluctuations by S/G pressure changes, this gain profile is implemented as the feedforward term in Figure 2.

4. Simulation Results

In order to evaluate the performance of the present S/G water level controller which is composed of the conventional PI control part and two feedforward terms.

The computer simulations were carried out using the simulator of KAERI. The results when the steam flow changes stepwise and with the following conditions

- Reactor power: 3%, 6%
- Turbine power: 0% (rolling)
- Reactor coolant temperature: 290°C, 295°C
- Feedwater temperature: 48°C, 58°C
- PI gains: $K_p=2$, $T_i=750$

are presented in the figures 5, 6, 7, and 8. Note that the PI gains are the same as the actual ones.

Figure 5, 7 shows the water level, steam flow, and feedwater flow behaviors using only the conventional PI controller. It is observed that the water level oscillates with large overshoot and undershoot. These are mainly due to sudden changes of S/G pressure followed by the swell and shrink phenom-ena. And moreover, the reverse control actions make worse the situation. Figure 6, 8 displays the responses using the present control scheme. Comparing to those of Figure 5,6 the magnitude of water level fluctuations is reduced, and it takes less time by about 2－4 minutes to stabilize the water level. These improvements are thought to be achieved by contributions of the feedforward terms.

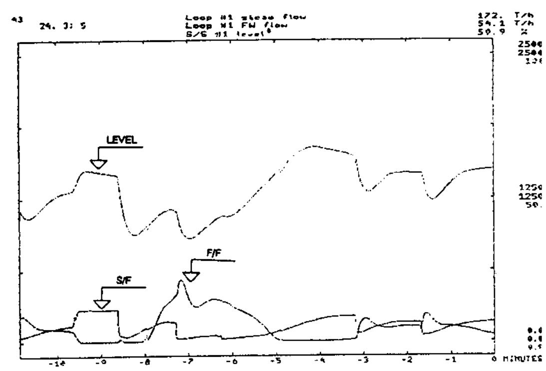

Fig. 5. Level, Steam Flow, Feedwater Flow Response by Conventional PI Controller 3% Power

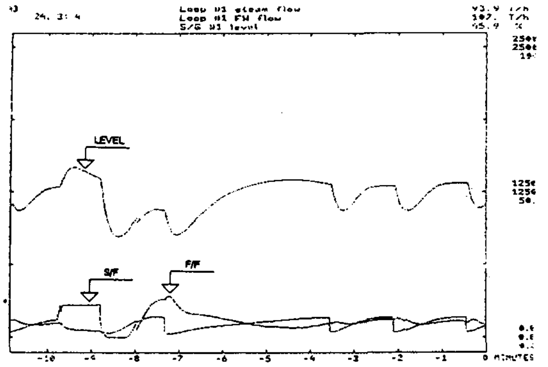

Fig. 6. Level, Steam Flow, Feedwater Flow Response by Proposed by Controller at 3% Power

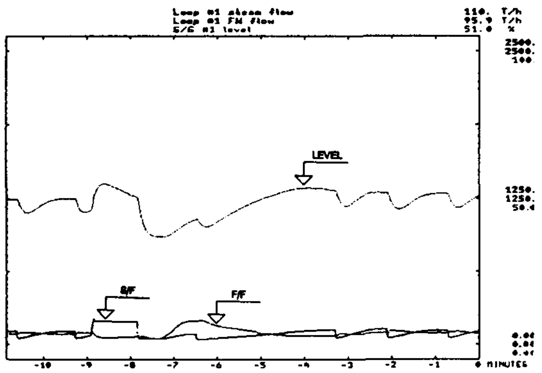

Fig. 7. Level, Steam Flow, Feedwater Flow Response by Conventional PI Controller 6% Power

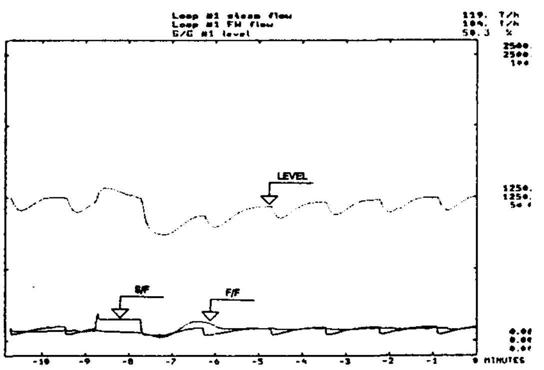

Fig. 8. Level, Steam Flow, Feedwater Flow Response by Proposed by Controller at 6% Power

5. Conclusion

In this paper, an improved S/G water level control scheme has been suggested, which in addition to the conventional PI control part, the feedforward terms using S/G pressure and feedwater temperature signals are included to explicitly account for the swell and shrink phenomena during the low power operation and transient states. To evaluate and compare the water level control performances, computer simulations were conducted using the simulator at KAERI. Resultingly, it was found that the present scheme leads to smaller level errors and quicker settling behavior than the conventional one.

Since the proposed control algorithm has been tested using the simulator which has the same characteristics as the commercial NPP, and the algorithm is easily adapted to a real system, we think that this study is valuable in the view of applications.

References

1. 구정의 외 "강제 운전정지 방안", NP−11, 한국원자력연구소, 1985.
2. 한국전력공사, "증기발생기 수위제어계통 개선, 1988. 12.
3. E. Irving, et al., "Towards Efficient Full Automatic Operation of the PWR Steam Generator with Water Level Adaptive Control", Boiler Dynamics and Control in Nuclear Power Station 2, British Nuclear Energy Society, pp. 309−330, 1990.
4. 한국원자력연구소, "Advanced Compact Nuclear-Simulator", 1988.