A Study on Reactor Thermal Power Calculation Methodologies Based on Feedwater Flowrate and Steam Flowrate for OPR1000 Plants

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1. Introduction

Most Optimized Power Reactor (OPR1000) plants use the secondary system calorimetric calculation method based on the feedwater flowrate as a Reactor Thermal Power (RTP) calculation method. However fouling phenomena of Venturi meters increase the measured pressure drop across the Venturi meter, thereby causing overestimation of the feedwater flowrate. As a result, RTP must be decreased to match the overestimated feedwater flowrate by Venturi meters to observe the operating nuclear power limit. To resolve this problem, the RTP calculation methodology based on the steam flowrate was additionally introduced at Yonggwang Nuclear Power Plant Unit 3&4 (YGN 3&4). However, it isn't yet clear how accurate the methodology based on the steam flowrate could be and which methodology is more reliable because the methodology based on the steam flowrate was just introduced last year for the first time. For this reason, we evaluated the reliability for these two methodologies and studied them to improve the accuracy of the measurement.

2. Methodologies for RTP Calculation

2.1 Methodology based on Feedwater Flowrate

In order to calculate the RTP based on the feedwater flowrate, it is needed to measure the feedwater flow detected by Venturi meters. Thus feedwater flowrate equation is defined as follows [1,2]:

$$W_{FWM} = k\left(\frac{YCd^2F_a}{\sqrt{1-\beta^4}}\right)\left(\frac{\sqrt{\Delta P_{FW}}}{V_{FW}}\right)$$

where

- W_{FWM} = measured feedwater mass flowrate
- k = constant
- Y = compressibility
- C = discharge coefficient
- d = diameter of Venturi throat
- F_a = area expansion factor
- β = diameter ratio (= d/D: Venturi throat/pipe)
- ΔP_{FW} = measured differential pressure by Venuri
- V_{FW} = specific volume

The amount of heat transferred to steam generators (SGs) is always balanced. Thus the reactor thermal power (Q_{FW}) based on the feedwater flowrate can be calculated as follows:

$$Q_{FW} = W_{MSC}h_{MS} + W_{BD}h_{BD} - W_{FWM}h_{FW}$$

where

- W_{MSC} = calculated steam flow ($= W_{FWM} - W_{BD}$)
- W_{BD} = SG blowdown flowrate
- W_{FWM} = measured feedwater mass flowrate
- h_{MS} = steam enthalpy
- h_{BD} = SG blowdown enthalpy
- h_{FW} = feedwater enthalpy

2.2 Methodology based on Steam Flowrate

Instead of the feedwater flowrate, the steam flowrate measured by SG outlet nozzles is used for the RTP calculation. Because the steam flow is measured by a differential pressure type instrument like a Venturi meter, the steam flowrate equation uses the same equation as the feedwater flowrate equation uses. However there are some differences compared with the feedwater flowrate calculation. For the calculations of area expansion factor (F_a), steam specific volume (V_S) and compressibility (Y) in the steam flow equation, safety class SG pressure meters are used. And also, the steam flowrate should be calibrated by the feedwater flowrate at the beginning of the fuel cycle when Venturi meters are not influenced with the fouling phenomenon because there is no way to remove steam outlet nozzles for calibrations. Thus, in order to calculate the steam flowrate (W_{MSM}), the main steam calibration factor (MSCF) is needed as follows [2]:

$$W_{MSM} = k\left(\frac{Yd^2F_a}{\sqrt{1-\beta^4}}\right)\left(\frac{2\sqrt{\Delta P_{MS}}}{V_S}\right) \times MSCF$$

where

ΔP_{MS} = differential pressure of SG outlet nozzle

In order to calculate the reactor thermal power (Q_{MS}) based on the steam flowrate, the measured steam flowrate (W_{MSM}) and the calculated feedwater flowrate (W_{FWC}) are used as follows:

$$Q_{MS} = W_{MSM}h_{MS} + W_{BD}h_{BD} - W_{FWC}h_{FW}$$

where $W_{FWC} = W_{MSM} + W_{BD}$

3. Reliability Evaluation

3.1 Methodology Uncertainty

When the RTP approaches the power operation limit, the power margin alarm (set at 100.5%) is produced. This alarm is designed to restrict the RTP exceeding above the safety analysis point (set at 102% including 1.5% uncertainty) [3]. According to the evaluation results [1,4] at the full power level of YGN 3&4, the uncertainties based on the feedwater flowrate and the steam flowrate are 0.969% and 1.34%, respectively. Considering the results, these two methodologies are acceptable.

3.2 Key Factors of Reliability

In the methodology based on the feedwater flowrate, the most significant factor is the Venturi fouling. A lot of plants in the inside and outside of the country experienced Venturi fouling problems that led to overestimation of RTP, with reduced generator output. If the opposite phenomenon occurs, underestimation of RTP can lead to an overpower incident leading to a reduction of the safety margins. Including the Venturi fouling problem, measurement errors lead to the false RTP calculation. Effects caused by the measurement errors are shown in Table I.

Table I: Effect by measurement errors

	Feedwater based RTP	Steam based RTP
Feedwater Flow ↑	↑	-
Steam Flow ↑	-	↑
Feedwater Temp. ↑	↓	↓
Steam Header pr. ↑	-	-
S/G pr. ↑	-	↑

3.3 Proposal to Improve the Reliability

As yet, there is no single method that is guaranteed to ensure perfect confidence in RTP measurement. Thus it is necessary to implement some sort of monitoring to confirm that measurement errors are not occurring. In order to support more reliable determination of RTP, operators should monitor key parameters and analyze trend. The parameters that are frequently used for trend analysis are:

- Feedwater flow
- Steam flow
- High Pressure(HP) turbine first-stage pressure
- Primary ΔT
- Feedwater temperature
- SG pressure
- Steam header pressure
- Gross electric power
- SG blowdown flow

Except for Venturi fouling, the methodology based on the feedwater flowrate is more accurate than the methodology based on the steam flowrate. Thus it is important to monitor Venturi fouling phenomena. HP turbine first-stage pressure is not influenced by Venturi fouling. Through monitoring the HP turbine first-stage pressure, we can early detect the Venturi fouling. The inlet turbine steam flow (Q_t) is directly linked to the total feedwater flow (Q_f). Thus, the relationship "$dQ_t = dQ_f$" applies because the SG blowdown flow (Q_b) and the auxiliary steam flow (Q_{aux}) are constant at full-load operating point. The deviation of the quantity $\left(E = \frac{dQ_t}{Q_t} - \frac{dQ_f}{Q_f}\right)$ between the beginning of the cycle and full-load operating point indicates that measurement errors have occurred

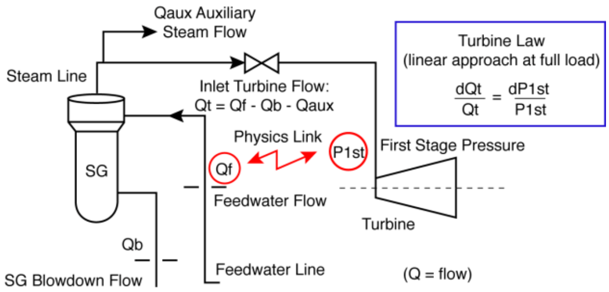

Fig.1. Monitoring for HP turbine first-stage pressure. [5]

4. Conclusion

In order to complement the weak point caused by Venturi fouling problems, the methodology based on the steam flowrate was introduced. However as yet there is no perfect confidence to confirm the early detection in the measurement errors. Thus it is very important to monitor and analyze related parameters. The efficiency of error detection is dependent on the monitoring and analyzing skills. Accurate estimation of the error is essential. The proposal to improve the reliability of RTP measurement is the easy way to be applied to the related systems. Through continuous monitoring and analysis for key parameters, we can expect the high level reliability of RTP measurement.

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