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Optimization of Dynamic Terms in Core Overtemperature Delta–T Trip Function

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노심 과온도 Delta-T 보호식의 동적보정함수 최적화

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Abstract

The characteristics of dynamic terms in the core overtemperature Delta–T trip function are investigated for various time constants and the effects on the trip setpoint are studied for the uncontrolled RCCA bank withdrawal at power event by using the NLOOP and the PUMA code. Based on this study, a procedure determining the optimal dynamic term is suggested and accordingly the optimum time constants are determined for the KORI 3&4 transition core. It reveals that the vessel average temperature lead–lag term is the most sensitive in DNB trip setpoint and the optimized time constants are 21 seconds for lead and 4 seconds for lag.

요 약

노심의 과온도 Delta-T 보호식에 설정된 동적보정함수들의 시정수 변화에 따른 특성이 조사되었으며, 출력운전 중 제어봉집합체의 비통제된 인출사고의 경우에 있어서 위 동적보정함수들의 과온도 Delta-T 보호식에 대한 영향을 시스템 코드인 NLOOP 및 노심열수력 코드인 PUMA를 사용하여 연구하였다.

위 연구를 바탕으로, 과온도 Delta-T 보호식의 동적보정함수에 대한 최적화 절차가 제시되었으며, 고리 3&4 호기 천이노심의 경우에 대해 최적화된 동적보정함수를 구하였다.

그 결과, 시스템의 최소 DNBR에 가장 영향을 줄 수 있는 동적보정함수는 노심평균온도에 대한 lead-lag 항으로 판명되었으며, 이때 최적화된 시정수값은 lead 시간 21초, lag 시간 4초로 나타났다. 이러한 동적보정함수의 최적화를 통하여 안전한계치를 변경하지 않고서도 노심의 운전영역을 개선할 수 있을 것으로 기대된다.

1. Introduction

In the Westinghouse–type nuclear power plants, the thermal overtemperature Delta–T (OT Delta–T) trip system functions to operate the reactor within DNB (Departure from Nucleate Boiling) design basis, hot–leg boiling limit, and coolant quality limit.[1] Thus the overtemperature Delta–T trip function is correlated with vessel temperature rise (Delta–T), vessel average temperature (T_{avg}), and primary system pressure. In this trip system, the dynamic compensation is necessary to account for the inherent delay in RTD (Resistance Temperature Detector) instrumentation and piping lags between the reactor core and loop temperature sensors.

The dynamic term of the OT Delta–T trip system directly affects the reactor trip time for the various kinds of events. Thus it is of great importance to optimize the dynamic term ensuring that the safety limits are bounded. Moreover, the optimization should be done in a way to improve the core operating region by reducing the likelihood of unnecessary reactor trip during normal operation such as a large load rejection. The determination of the optimum value requires transient analyses and sensitivity studies based on a digital simulation of the complete NSSS (Nuclear Steam Supply System) since the time constants in the dynamic terms are plant dependent.[1]

The objective of this paper is firstly to investigate the characteristics of the dynamic terms in the OT Delta-T trip function by using FORTRAN program DYNA which was developed to estimate the dynamic responses to various control inputs and analyze the sensitivity of the dynamic terms in case of the uncontrolled RCCA bank withdrawal at power. Based on the above results, a procedure determining the optimal OT Delta-T dynamic term will be suggested and finally the optimum time constants for the KORI 3&4 transition core will be calculated according to this procedure.

2. The Characteristics of Dynamic Term

The dynamic terms used in the OT Delta-T trip function are necessary for the following reasons: [1]

1) To compensate RTD instrumentation time delay measured during plant startup tests,
2) To offset piping lags including RTD bypass-loop delay and bypass-pipe heat-capacity effects,
3) To decrease the possibility of an unnecessary reactor trip following a large load rejection,
4) To ensure the protection system response being within the limits required for the accident analyses.

These dynamic compensation terms consist of three typical control functions such as lead/lag, rate/lag, and noise filter(lag).

Their characteristics are described by Transfer Function[2] which is defined as;

$$G(S)=\frac{C(S)}{R(S)} \tag{1}$$

where, R(S) : Laplace Transformation of input

C(S) : Laplace Transformation of output

S : Laplacian operator.

The output function C(S) can be expressed in the time domain using the inverse Laplace Transformation, that is,

$$C(t)=L^{-1}[G(S)\times R(S)] \tag{2}$$

Here, the Transfer Functions for each control unit is expressed as follows:

1) Lead-Lag unit

$$G(S)=\frac{1+\tau_1 S}{1+\tau_2 S} \tag{3}$$

2) Rate-Lag unit

$$G(S)=\frac{\tau_1 S}{1+\tau_2 S} \tag{4}$$

3) Noise Filter (Lag) unit

$$G(S)=\frac{1}{1+\tau_1 S} \tag{5}$$

where, τ's are time constants.

The lead-lag unit has a function to amplify the input signal as much as τ_1/τ_2 at the initial stage and then make the output converge gradually to the original input values. On the other hand the rate-lag unit enforces the output to decay out without any amplification of the input signal at the initial stage. The lag unit provides a gradual response to a rapid input and thus it is commonly called noise filter. In general, the rate-lag unit is not employed in the OT Delta-T trip function because the other two units are sufficient in securing the safety boundaries and the reactor operability.

A FORTRAN program DYNA[2] had been developed in order to evaluate the characteristics of each dynamic term for the various control inputs and time constants.

For the lead-lag unit, sensitivity study has been performed with varing the lead and lag time con-

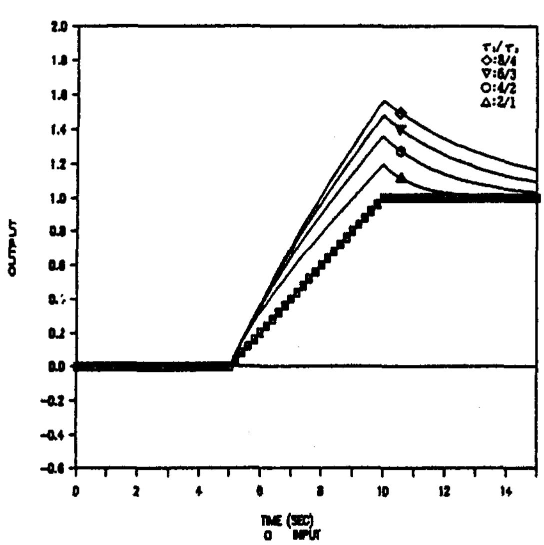

Fig. 1. Lead-Lag Response for Ramp Input

stants and taking the ramp function as an input-(Fig. 1). It shows that the higher the lead time constant (τ_1), the faster the output response and the higher the lag time constant (τ_2), the later the output decay. Consequently, it illustrates that selecting the proper lead time constant is important since an increase in lead time constant may cause more noise in the output signal.

3. Optimization of Dynamic Terms

The Optimization of the dynamic terms in the OT Delta–T trip function requires detailed transients analyses and sensitivity studies for the specific plant since the time constants in the dynamic terms are dependent on plant type.

In general, the uncontrolled RCCA bank withdrawal at power is a typical accident which generates the most sensitive transient conditions regarding the OT Delta–T trip signal.[4] The event is chosen for the sensitivity study of the OT Delta–T dynamic terms, and based on the study an optimization procedure is established.

The uncontrolled RCCA bank withdrawal at power is classified as an ANS Condition II event.[5] The event is caused generally by the misoperation of the control rod banks wired in common each other and thus a wide range of reactivity insertion rates and initial operating powers should be considered in the transient analysis. The sensitivity study on this event was performed for the KORI 3&4 reload core by using the system transient code NLOOP[6] and the core thermal hydraulics code PUMA.[7] The initial and boundary conditions adopted in this analysis are the same with those of KORI 3&4 RTSR(Reload Transition Safety Report)[8] and summarized in Table 1.

Table 1. Summary of Initial & Boundary Conditions

○Reactivity Coefficients	100%/60%
–MTC(pcm/C)	0.0*/10.0**
–DTC(pcm/C)	–1.6
○Initial NSSS Power(Mwt)	2785/1671
○Total Coolant Flow(Kg/s)	13620
○Vessel Average Temperature(C)	309.2/302.17
○Pressurizer Pressure(bar)	155.13
○Pressurizer Water Volume(m^3)	22.71/17.65
○Feed Water Temperature(C)	226.6/200.7

*Minimum Feedback for Full Power
**Minimum Feedback for Low Power

The OT Delta–T trip setpoint equation used for the KORI 3&4 plants is as follows:

$$\Delta T\left(\frac{1+\tau_1 S}{1+\tau_2 S}\right)\left(\frac{1}{1+\tau_3 S}\right)<$$
$$\Delta T_0 \{K_1-K_2\left(\frac{1+\tau_4 S}{1+\tau_5 S}\right)$$
$$\left[T\left(\frac{1}{1+\tau_6 S}\right)-T'\right]+K_3(P/P')-(\Delta I)\} \quad (6)$$

where,

ΔT : Measured vessel temperature difference
ΔT_0 : Indicdted ΔT at rated power
T : Vessel average temperature
T′ : Vessel average temperature at full power
P :Pressurizer pressure
P′ : Pressurizer pressure at full power
f(ΔI) : Axial offset, a function of the neutron flux

between upper and lower long ion chambers

S : Laplacian operator

K_1, K_2, K_3 : Constants

$\tau_i, i=1-6$: Time Constants

3. 1. Analysis Procedure

The OT Delta–T trip setpoint equation for the KORI 3&4 plants has 4 dynamic terms: two lead–lag terms for Delta–T and T_{avg} and two noise filters for Delta–T and T_{avg}.

In order to exactly determine the optimal dynamic term, many cases of sensitivity studies are required for the above 4 dynamic terms. For simplicity, a preliminary study was performed for the full power (100%) case. This sensitivity study was conducted with varing the time constants given in the equation (6). The five cases of time constants used are listed in Table 2. Fig. 2 illustrates the results of the minimum DNBR vs. reactivity insertion rate which are generated by the OT Delta–T trip and high neutron flux trip. It reveals that the minimum DNBR lines resulted from the OT Delta–T trip continuously decrease as the reactivity insertion rate increases. This tendency ceases at the least minimum DNBR point from which the high neutron flux trip starts (break point). Obviously, the minimum DNBR lines portrayed by the high neutron flux trip are not dependent on the time constants. It also shows that the difference of minimum DNBR between the RTSR case and case 2 (no Delta–T lead–lag) is smaller than the difference between the RTSR case and case 5 (static) within the OT Delta–T trip range, and the case 3 (no Delta–T and no T_{avg} lead–lag) line is almost identical to the case 4 (no T_{avg} lead–lag) one. This means that the effect of Delta–T lead–lag on the minimum DNBR is much less than that of T_{avg} lead–lag. Fig. 2 also illustrates that the effects of two noise filter constants (case 2 and case 3) are relatively small as compared to those of the two lead–lag time constants.

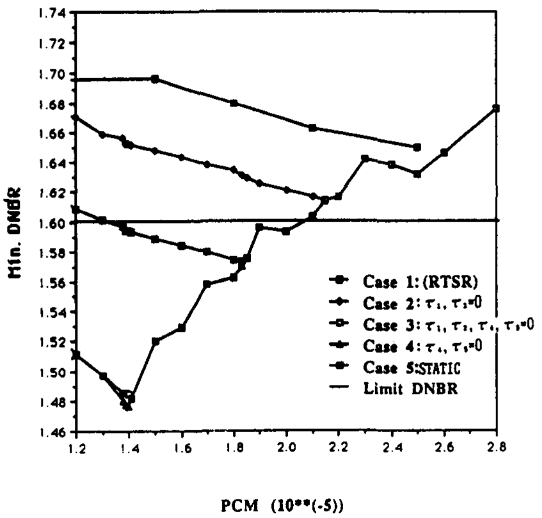

Fig. 2. Minimum DNBR Lines by OT Delta–T Trip and High Neutron Flux Trip (at 100% Power)

From the facts mentioned above, it is found that the T_{avg} lead–lag term is the most important parameter affecting the DNB trip setpoint. Therefore, the sensitivity study will focus on the T_{avg} lead–lag term, assuming the other dynamic terms to be fixed as given in the RTSR. (see Table 2)

Table 2. Time Constants for 5 Cases Used in The OT ΔT Trip Setpoint Equation (unit; sec)

TIME / CASE	τ_1	τ_2	τ_3	τ_4	τ_5	τ_6
Case 1*	12	3	4	22	4	4
Case 2	0	0	4	22	4	4
Case 3	0	0	4	0	0	4
Case 4	12	3	4	0	0	4
Case 5	0	0	0	0	0	0

*Case 1 : RTSR

2.2. Full Power (100%) Case

In Fig. 2, it is shown thatthe reactivity insertion rate causing the limit DNBR (1.60) is 2.1 PCM. Therefore, the dynamic time constants resulting the minimum DNBR equal to 1.60 will be sought in near of that point.

The minimum DNBR's versus reactivity insertion rates were calculated with varing the lead and lag time constants of T_{avg} lead–lag term for the case 1 at full power (Fig. 3 and Fig. 4). These figures show that the minimum DNBR increases as the lead time constant increases and decreases as the lag time constant increases. Further sensitivity calculations were performed to search the optimum time constants, varing both the lead and the lag time constants. the results are presented in Fig. 5. From this figure, it is found that the optimal T_{avg} time constants ratio (τ_4/τ_5) should be 15/3. These time constants result in the least minimum DNBR 1.603 at 2.1 PCM where the OT Delta–T trip & high neutron flux trip signals are concurrently actuated (break point).

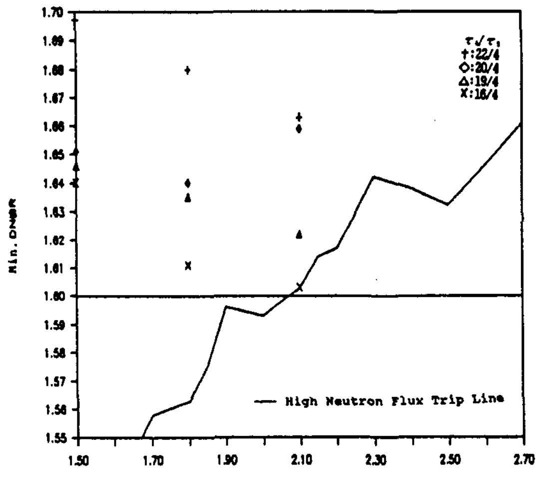

Fig. 3. Minimum DNBR vs. Reactivity Insertion Rate for the Various τ_4 (Case 1, at 100% Power)

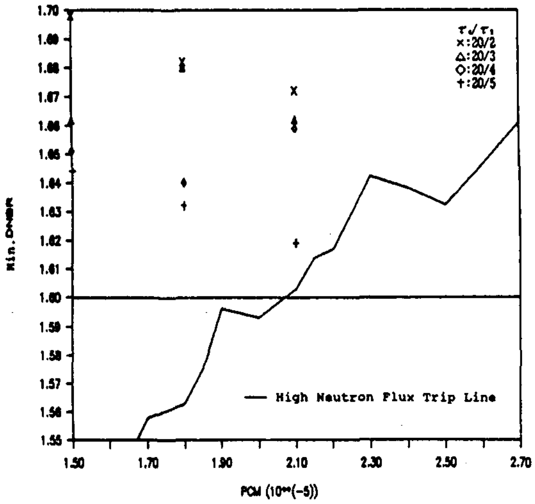

Fig. 4. Minimum DNBR vs. Reactivity Insertion Rate for the Various τ_5 (Case 1, at 100% Power)

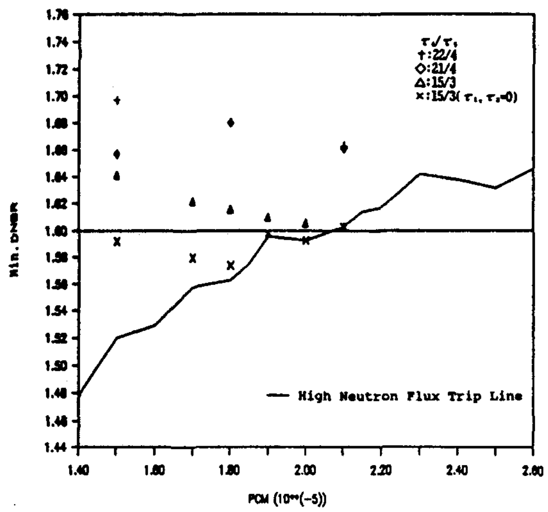

Fig. 5. Optimization of τ_4 and τ_5 at 100% Power

3. 3. Low Power (60%) Case

By the similar way to the full power case, the reactivity insertion rate causing the limit DNBR (1.60) was found to be 2.8 PCM for the 60% power case. Therefore, the sensitivity study in near of 2.8 PCM was performed to find the optimal T_{avg}

lead–lag term.

Fig. 6 shows that the T_{avg} lead–lag term, 15/3, cannot be the optimal time constants any more for low power case. The optimal T_{avg} time constants should be 19/3 or 21/4. Here, the time constants 19/3 would not be appropriate because the higher lead–lag time ratio (6.3) may increase noise. Therefore, the optimal T_{avg} lead–lag term in the OT Delta–T trip setpoint equation is chosen to be 21/4 for low power case.

In order to check reactor operability, the transient DNBR behaviors for three cases of T_{avg} lead–lag terms including the RTSR case were calculated (Fig. 7). This shows that the improvement in the operation region is expectable without any influence on the safe operation, even if the T_{avg} lead–lag constants 22/4 used in the RTSR is adjusted to 21/4.

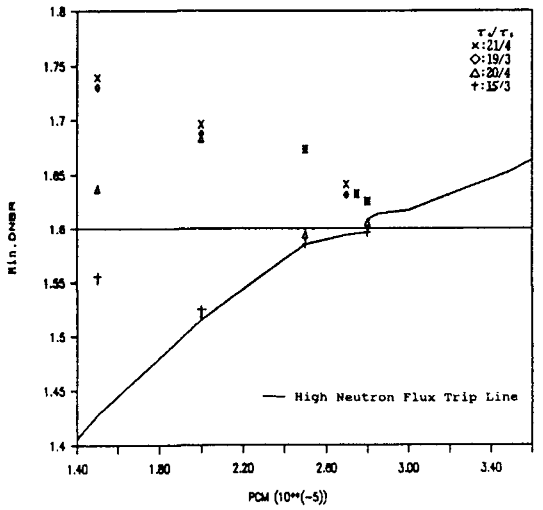

Fig. 6. Optimization of τ_4 and τ_5 at 100% Power

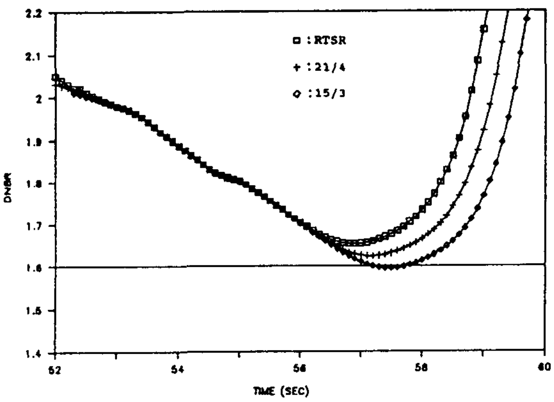

Fig. 7. DNBR Transient Behavior for Three T_{avg} Lead–Lag Time Constants (Case 1, at 60% Power)

5. Conclusions

The characteristics of dynamic terms used in the Overtemperature Delta–T (OT Delta–T) trip function were investigated and the sensitivity studies for the dynamic terms in case of the uncontrolled RCCA bank withdrawal at power event of the KORI 3&4 transition core were performed in order to suggest an appropriate procedure determining the optimal dynamic term and to optimize the time constants of the dynamic term.

As a result of this study, it has been concluded that

1) The most important dynamic term that affects system transient is the T_{avg} lead-lag term, and the suggested optimization procedure for the OT Delta–T dynamic terms is as follows :

 i) Firstly, obtain high neutron flux trip line in coordinate of minimum DNBR vs. reactivity insertion rate.

 ii) Secondly, obtain the reactivity insertion rate (PCM) at the cross point of high neutron flux trip and the limit DNBR (1.60) line.

 iii) Finally, find the optimal T_{avg} lead–lag time constants which results in the limit DNBR at the reactivity insertion rate obtained from the second step.

2) the optimal T_{avg} lead-lag time constants for the KORT 3&4 transition core are 21 seconds for lead and 4 seconds for lag. By this optimization, the core operation region is expected to be improved without changing the core safety limits.

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