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Proposal for Increase of Thermal Margin in COLSS

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ABSTRACT

One of the most important constants to be installed in COLSS, a monitoring system in CE typed reactors, is ROPM which would limit the operating space. This static ROPM was calculated from digital transient analysis assuming that every design basis transient was initiated from the most severe initial condition combination (LCO). Once it could be assured that core condition would not be located at none other than LCO, this static ROPM could be replaced with dynamic ROPM calculated at that condition and the dynamic ROPM would be definitely less than the static ROPM. In order to do, it must be required to calculate the transient discrete sensitivity parameters and parameters change distribution. The purpose of this report is just to propose the enlargement method for thermal margin.

1. Introduction

One of the biggest and most important concerns in Nuclear Power Plant Operation might be a plant operation margin. The efforts for increase in thermal margin has been going on even now in the world. However so, it could not be infinitely expanded because the space explained as a set of operating points must be mainly depends on system hardware. In view point of this, the space (Available over power margin) consists of thermal margin and minimum over power margin which can cover the AOOs events and might be called a constraint condition for operating space.

In Korea, some devices were tried to increase thermal margin which could be divided by a means of approach basis into three parts , such as control of uncertainty, improvement of model, and partitioning of application range. Lately margin concerns must become more highlighted for future plants. As a pre-eminent problem, KINS starts to newly interprets the meaning of Loss of Offsite Power as a analysis basic condition rather than as a single failure. What is worse is to assume that LOOP will occur simultaneously at time of reactor trip. If this LOOP was applied for Non-LOCA analysis, plant would be required to hold extra margin to accommodate the margin loss due to LOOP. Considering the fixed margin constraint space, thermal margin must be rather reduced as much as LOOP margin loss. In high interesting about Next Generation Reactor, furthermore, it must be focused that one of the important design requirements is the insurance of thermal margin greater than 15%.

In these veins, any kinds of approach to thermal margin problem must be necessary and completed economically and safely. The purpose of this report is just to introduce an idea of Adjoint Sensitivity Method application to this problem and to discuss its feasibility with some experts.

2. Digital Transient Analysis and COLSS

CE-typed reactor has digital computers COLSS/CPCs for monitoring and protection system, respectively. The CE Non-LOCA analysis determines the constraint conditions (ROPM, set points, CPCs digital filter coefficients) so that COLSS/CPCs appropriately work which is the reason called DTA.

Of these constants, ROPM would be installed in COLSS which ensure that core operating conditions remain in LCO. DNB SAFDL violation would not be intimidated from any transient of AOOs starting within LCO, because the largest ROPM calculated from the most severe boundary condition for every design basis event will be installed in COLSS. But considering the case of normal operating condition of real plant, it might be too conservative.

3. Comparison of CE and WH analysis approach

Comparison of analysis approach in CE and WH is helpful to understand what is focused in this study. As previously mentioned, one of the most important and cumbersome work in CE analysis is to calculate ROPM because every design basis events should be analyzed under the most severe conditions. What can make this necessary is the on-line core condition monitoring system, COLSS, which can contribute to expand the operating margin and to display it in monitor through explicit DNBR calculation.

For WH-typed reactor, nominal condition, which will be also in LCO range, are usually selected as an initial condition for analysis, and the applied trip functions are very extreme response and implicit potentialness, OP△T and OT△T. These two elements caused WH plants LCO to be narrow, whereas it is easier to analyze WH Non-LOCA transient analysis. But thermal margin contained implicitly in OP△T and OT△T function is apparently less than COLSS.

4. Final Goal of Protection/Monitoring System

The future power plant is supposed to be equipped with more digitalized system and far more advanced protection/monitoring system, for example, the auxiliary on-line calculator which can generate physics data. Once it is possible to calculate inside core condition and T/H behavior, on-line digital transient analysis could be possibly executed, even though not completely correct. It would be safe to say that development of such system which can simultaneously perform core physics analysis as well as transient analysis is expected as a final goal of protection and monitoring system. What can be get from this on-line system? It would be possible to predict the on-line calculated transient ROPM less than or equal to static ROPM.

5. Similar Approach

A starting point which gives this idea is that the static ROPM calculated under the most severe conditions must be greater than or equal to any dynamic ROPM calculated at a core condition within LCO. Thus, if it could be assured that core condition is not along the line of LCO, static ROPM could be replaced with dynamic ROPM. Then, as a result, thermal margin will be increased as much as the difference between these ROPMs at least at that core condition.

Some similar approaches were proposed in COLSS input installation, for example, ROPM as a function of ASI (in case of strong dependency on ASI), the scram curve corresponding to analysis power shape instead of fixed bottom peaked one, and/or complete set (time vs. flow) of flow coast down curve. These approaches are means as a part of Best Estimate and give opening of strong application of on-line system.

6. Semi-on-line ROPM Calculation

At the present technology and regulation state, it is impossible to analyze complete-on-line core transient. Even if allowed to do so, development of method to be applied will be also a big problem.

However ,it could be possible to calculate semi-on-line dynamic ROPM which is a limited and not complete-on-line ROPM calculation if some necessary and sufficient conditions are satisfied. Suppose that a nominal plant condition (e°) could be specified in on-line monitoring system and the dynamic ROPM was calculated at this condition, in which dynamic ROPM had to be definitely less than static ROPM. Then, this dynamic ROPM will be valid, as long as core condition would not be changed (weak condition).

During an actual operation, core condition will and can not be fixed, but can be in usually steady state. Consider another core condition ($e^{\circ} + \delta e$), which is also in steady state, apart from previous one. Now what should be done is to calculate dynamic ROPM at another condition ($e^{\circ} + \delta e$).

If sensitivity parameters valid at neighborhood of e° and distribution of $\delta \varepsilon_i$ could be calculated at every discrete transient time, dynamic ROPM ($e^{\circ} + \delta e$) can be obtained as:

$$ROPM(e^{\circ} + \delta e) = ROPM(e^{\circ}) + \Sigma \int_0^{t_f} \frac{\partial ROPM}{\partial \varepsilon_i} \delta \varepsilon_i dt \qquad \textbf{6-1}$$

That is, $ROPM(e^{\circ}) \le ROPM(e^{\circ} + \delta e) \le$ Static ROPM along the line of LCO

In this approach, the big problems are how to calculate the sensitivity parameters and what conditions to be applied (necessary and sufficient conditions). The related method for sensitivity parameters evaluation and condition to be applied will be discussed in following sections.

6-1. Response Surface Method

There is a general method to make a response surface usually applied for unknown parameters which is usually done through lots of simulation by changing system parameters such as boundary condition and coefficients in mathematical model. After making a response distribution and probabilistic treatments, sensitivity parameters would be obtained. Whereas this kind of approach could be applied without limits, it usually required tremendous computing time and the results must contain still unnecessary conservatism. Because the indirect effect term, nonlinear term, was ignored resulting from fixing any other system parameters.

6-2. Adjoint Sensitivity Method[1]

In order to analyze a transient, approximated and simplified (linearizing) math. model was usually used. If the model was defined in special metric space, Banach space[2] and Hilbert space[3] with its unique non-linearity, and main parameter we concerns with was defined in any canonical form, these sensitivity parameters could be obtained more easily and robustly. Of course there are some limiting conditions for application. As long as these conditions are satisfied, this approach was valid however these operator and functional are non-linear. Let R represent the parameter, DNBR,

$$R=DNBR=f(ASI,\ T_{inlet}, \mathrm{Press}, Power, Fr, Flow=e), \qquad \textbf{6-2-1}$$

where f is a nonlinear functional in e.
If R is linear in h and VR(e;h) is continuous, VR[4] could be represented as $VR=R'_u h_u+R'_\alpha h_\alpha$, where $R'_u h_u$ and $R'_\alpha h_\alpha$ are called indirect effect term and direct effect term, respectively. There are two alternative method to achieve this terms. In this report Adjoint Sensitivity Method was introduced. The range of R must be scalar field (Λ) , which is the range space of functional f mapping at the domain e, that is, $f:D \subset E \rightarrow \Lambda$ (f:nonlinear functional).

The system and boundary conditions could be expressed in general operator term,

$$N[u(x), \alpha(x)] = Q[\alpha(x)], \text{ and}$$
$$B[u, \alpha] = A(\alpha), \qquad \textbf{6-2-2}$$

where $N:S\subset E \rightarrow E_Q$ (N:non-linear operator)
It is easy to guess that $R'_u h_u$ could be expressed in terms of h_α and known value (initial and boundary condition) through the elimination of the unknown values of h_u from the expression giving the sensitivity VR(e;h) of R(e) at e° . After G-differential[5] and adjoint operator application, Riesz theorem[2] finally ensure that $R'_u h_u$ was uniquely calculated as following, $L^*(e^\circ)v=\nabla_u R(e^\circ)$. The construction of the desired adjoint system has been completed:

$$DR(e^\circ : h) = R_\alpha' h_\alpha + (v, VQ(e^\circ : h) - N_\alpha' h_\alpha) - P[h_\alpha, v; e^\circ] \qquad \textbf{6-2-3}$$

7. Conceptual Simple Example

This on-line transient DNBR prediction method was just only conceptually applied for Loss of Flow event as a simple example. This transient is a typical one for flow decrease. Simultaneous four RCPs coast down resulted from complete loss of electric power to RCP produce pressure and coolant temperature increase within a few seconds. Reactor trip signal was generated by RCP shaft low speed trip. That is, margin degradation due to flow decrease was mitigated by power reduction from reactor trip. In real transient analysis, it was assumed that only power and flow were changed, remaining parameters were fixed for conservatism and in nature of transient characteristics. Futhermore, flow coastdown was used in table type (time vs. flow). Using the adjoint sensitivity method, the desired sensitivity parameters at discrete transient time for this event starting from initial condition e° could be calculated,

$$\frac{\partial R}{\partial \varepsilon_i} \quad i=1,\ldots 6 \qquad \text{7-1}$$

Of system parameter change distribution used in the analysis, flow curve was completely independent on transient and power change also was almost independent. For detail explanation, typical DNBR transient for loss of flow event was showed in Figure 1. Now, it would be possible to calculate DNBR for transient initiated from e° $+\delta$e, for point A($\lim_{\Delta t \to 0} \delta e(\Delta t)$),

$$\begin{aligned} \Delta DNBR \simeq {} & \frac{\partial DNBR}{\partial \mathrm{Press}} \Big|_{t=0} * \delta press + \frac{\partial DNBR}{\partial ASI} \Big|_{t=0} * \delta ASI + \frac{\partial DNBR}{\partial Fr} \Big|_{t=0} * \delta Fr + \\ & \frac{\partial DNBR}{\partial Tinlet} \Big|_{t=0} * \delta Tinlet + \frac{\partial DNBR}{\partial Power}(t) \Big|_{t=0} * \delta Power(t)\Delta t + \\ & \frac{\partial DNBR}{\partial Flow}(t) \Big|_{t=0} * \delta Flow(t)\Delta t \text{ , and} \end{aligned} \qquad \text{7-2}$$

for critical point B,

$$\Delta DNBR \simeq \sum_{i=1} \frac{\partial DNBR}{\partial \varepsilon_i} \Big|_{t=\tau} * \delta \varepsilon_i + \sum_{j=1} \int_0^{\tau} \frac{\partial DNBR}{\varepsilon_j}(t)\, \delta \varepsilon_j(t) dt \qquad \text{7-3}$$

8. SUMMARY

As a begining atage, a theoretical approach for semi-on-line ROPM was proposed in this paper. If a substantial increase in thermal margin is required in a digital plant, this approach would be very meaningful and valuable. To complete this method, there should be some limiting conditions to be specified more strongly and explicitly.

And the epochal thermal margin increase is not expected without change of conservative logic in COLSS/CPCs as long as the AOPM related to hardware was fixed.

9. Reference

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Figure 1. Transient DNBR Curve for loss of flow event