Loading Pattern Optimization by Multi-Objective Simulated Annealing

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1. Introduction

The simulated annealing (SA) algorithm [1,2] has been popularly adopted for the optimum fuel assembly (FA) loading pattern (LP) search calculations in initial/reload core design of light water reactors. However, it has a major drawback of long computing time because it requires neutronics evaluation of tens of thousands of trial LPs in the course of the optimization. In our previous work, we introduced a screening technique (ST) base on 2D model aimed at reducing computing time for SA LP optimization with 3D model [3] and we defined a multi-objective function, in which we didn't distinguish the main objective term and the penalty terms related to the constraints. We used the same form of the function for all the terms and we normalized each term so that each term has similar importance [4].

In this paper, we added one term on that multi-objective function and applied the multi-objective function to SA optimization calculations using Young-Gwang unit 4 (YGN4). The ST introduced in the previous work was also adopted in this work.

2. Multi-Objective function

In applying SA algorithm to the optimum LP search for an initial/reload core, one characterizes first an objective function fit for the initial/reload core design requirements. Equation (1) below shows a multi-objective function, $J(X)$, appropriate for design requirements of the pressurized water reactor core.

$$\begin{aligned} J(X) &= w_L J_L(X) + w_R J_R(X) + w_Q J_Q(X) \\ &\quad + w_B J_B(X) + w_Z J_Z(X) + w_F J_F(X) \end{aligned} \quad (1)$$

Where
w_L : weight for the cycle length,
w_R : weight for the 2D pin power peaking factor,
w_Q : weight for the 3D pin power peaking factor,
w_B : weight for the pin discharge burnup,
w_Z : weight for the HZP MTC,
w_F : weight for the HFP MTC,
$J_L(X)$: normalized cycle length function,
$J_R(X)$: normalized 2D PPPF function,
$J_Q(X)$: normalized 3D PPPF function,
$J_B(X)$: normalized pin discharge burnup function,
$J_Z(X)$: normalized HZP MTC function,
$J_F(X)$: normalized HFP MTC function.

The multi-objective function, $J(X)$, in Eq. (1) is defined as a linear combination of six objective functions. Each objective function is defined as follows and Y represents R , Q , B , Z and F :

$$J_L(X) = \begin{cases} 1 + \frac{1}{\overline{L}}\left(L(X) - L_{\lim}\right)^2 & \left(L(X) < L_{\lim}\right) \\ 0 & otherwise \end{cases}$$
$$J_Y(X) = \begin{cases} 1 + \frac{1}{\overline{Y}}\left(Y(X) - Y_{\lim}\right)^2 & \left(Y(X) > Y_{\lim}\right) \\ 0 & otherwise \end{cases} \quad (2)$$

Where
$L(X)$: cycle length of LP X ,
$R(X)$: 2D PPPF of LP X during the cycle,
$Q(X)$: 3D PPPF of LP X during the cycle,
$B(X)$: maximum pin discharge burnup of LP X ,
$Z(X)$: MTC of LP X at BOC HZP,
$F(X)$: MTC of LP X at BOC HFP,
$L_{\lim}$: minimum target cycle length,
$R_{\lim}$: 2D pin power peaking limit,
$Q_{\lim}$: 3D pin power peaking limit,
$B_{\lim}$: pin discharge burnup limit,
$Z_{\lim}$: HZP MTC limit,
$F_{\lim}$: HFP MTC limit,
$\overline{L}$: normalization factor for the cycle length,
$\overline{R}$: normalization factor for the 2D pin peaking,
$\overline{Q}$: normalization factor for the 3D pin peaking,
$\overline{B}$: normalization factor for the pin discharge burnup,
$\overline{Z}$: normalization factor for the HZP MTC,
$\overline{F}$: normalization factor for the HFP MTC.

3. Results

The multi-objective function of Eq.(1) is implemented in UNCARDS(Unified Nodal Code for Advanced Reactor Design and Simulation). In order to examine its validity, LP optimization calculations were performed for the initial and reload cores of YGN4. The same constraints except minimum target cycle length were used for 4 problems of initial and reload cores. As the design constraints, the 2D PPPF limit of 1.5 and the 3D PPPF limit of 2.2 were imposed for all the FA's. The pin discharge burnup limit was set as 58000MWD/T. The upper limits of BOC MTC were set as 5.0 $\text{pcm}/^{\text{O}}\text{F}$ and 0.0 $\text{pcm}/^{\text{O}}\text{F}$ for HZP and HFP, respectively. The minimum target cycle lengths were set as 14143, 9740, 14060 and 13365[MWD/T] which were real cycle lengths, respectively. Table 1 shows the results of the 4 independent SA optimization calculations. Efficiency of ST was 18.1, 25.3, 53.8 and 44.2 for those optimization calculations, respectively. Table 2 summarizes the design parameters of the optimum LP's obtained from 4 independent SA optimization calculations. The four LP's were operated approximately 3, 29, 7 and 40 days longer than real LP's, respectively. Figure 1 shows the real LP's and the LP's obtained from SA optimization calculations.

4. Conclusion

In this paper, we redefined the multi-objective function for LP optimization by SA. We applied the multi-objective function to SA optimization calculation for the initial and reload cores. We obtained an optimum LP from an optimization run for each cycle. We observed that all the optimum LPs satisfy all the design constraints.

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Table 1 Results of the 4 independent SA optimization calculations

	No. of LP's Stages	No. of LP's Accepted	No. of LP's Sampled	No. of 3D Evaluations	No. of LP's Screened out	ST Eff.(%) [a)]
Initial core	76	4570	16697	13679	3018	18.1
Cycle 2 core	90	4895	30164	22532	8232	25.3
Cycle 3 core	57	3881	19915	9195	10720	53.8
Cycle 4 core	53	4014	12730	7106	5624	44.2

a)(1- No. of LP's Screened out / No. of LP's Sampled) $\times$ 100

Table 2 Design parameters of the 4 optimum LP's

	$R(X)$ <1.5	$Q(X)$ <2.2	$Z(X)$ <5.0 [a)]	$F(X)$ <0.0 [a)]	$L(X)$ [b)]	L_{lim} [b)]	$\Delta L(X)$ [c)]	Δ EFPD [d)]
Initial LP	1.485	2.110	4.019	-5.107	14246	14143	103	3
Cycle 2 LP	1.495	1.760	1.562	-13.506	10826	9740	1086	29
Cycle 3 LP	1.494	1.786	2.871	-11.112	14333	14060	273	7
Cycle 4 LP	1.496	1.784	3.903	-10.372	14855	13365	1490	40

a) $\text{pcm}/^{\text{O}}\text{F}$ b) MWD/T c) $L(X)$ - L_{lim} d) Δ effective full power days

Figure 1 Real LP's and the optimum LP's for the initial/reload core of YGN4