OPTIMIZATION OF BWR CONTROL ROD PATTERN FOR RELAXED ROD SEQUENCE EXCHANGE

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ABSTRACT

Control rod pattern optimization for relaxed rod sequence is obtained by a combination of dual feasible search method as a local optimum search engine and a set of knowledge based rules as a global optimum search engine. The local optimum search considers all constraints encountered in an experienced manual rod pattern design. The global optimum search rescues the local search trapped in a local minimum using a set of rules deducted from practical rod pattern design experiences. A whole cycle rod pattern design utilizing a relaxed rod sequence exchange interval is targeted with the goal of maximizing cycle energy. The resulting methodology interfacing with the MICROBURN–B2 core simulator generates rod patterns with a quality equal to or better than an expert manual design.

I. Introduction

Control rod patterns for modern BWR fuel cycle designs are increasingly utilizing the concept embodied in the relaxed rod sequence (RRS) exchange.(1) In RRS, a control rod sequence (A1, A2, B1, or B2) may last two or three times longer than the conventional sequence of 1000 MWd/MTU exchange interval. Despite its longer exchange interval, control cells in a RRS core loading may contain fresh fuel bundles as well as once or twice burned fuel bundles. A modern BWR fuel cycle design typically relies on high gadolinia concentration for longer cycle length (18 or 24 months). This means that the fresh fuel bundles in a RRS core generally go through large transition in reactivity during their early operation. Thus a control rod pattern that works well for the beginning of a rod sequence may not work for later exposure points within the same sequence. For this reason, the optimization of control rod patterns for a RRS core design is more difficult than that for the conventional core design. Another layer of difficulty is found in controlling thermal margin at the end of cycle (EOC) under all–rod–out (ARO) condition. At this point, the available thermal margin for a given core loading is largely dependent on the previous control rod patterns.

Additional constraints include a computing time required to be competitive with experienced manual design and a cycle energy required to be equal to or better than a highly optimized manual design. The cold shutdown margin constraint is not considered within the proposed method as it is closely tied to the loading pattern. This paper presents a practical control rod pattern optimization method dealing with these difficult issues.

II. Methodology

II.A Local Optimum

A rod pattern optimization presented here consists of a mathematical search engine (MSE) and a set of knowledge based rules (KBRs). MSE provides a fast convergence to a local optimum. KBRs provide a mechanism to escape from a local minimum trap. MSE solves a local optimization problem defined by the following objective and constraints at a given cycle exposure point:

<u>Objective</u>

$$J(R) = \sum \left(P_{r,i}(R) - P_{t,i}\right)^2$$

where
R = control rod pattern vector (control rod position vector)
$P_{r,i}$ = radial bundle power at core location i
$P_{t,i}$ = target radial bundle power at core location i

<u>Reactivity Constraints</u>

$$C_{\rho,u}(R) : \rho(R) – \rho_t \leq \delta\rho_u$$

$$C_{\rho,l}(R) : \rho_t – \rho(R) \leq \delta\rho_l$$

where
ρ = k–effective or core inlet flow
ρ_t = target k–effective or core inlet flow
$\delta\rho_x$ = operational allowance for target k–effective or core inlet flow upper (x=u) or lower (x=l) deviation

<u>Axial power Shape Constraint</u>

$$A_p(R) : \left|AO_p(R) - AO_t\right| \leq \delta A_p$$

where
AO_p = axial power tilt
AO_t = target axial power tilt
δAO_p = operational allowance for target axial power tilt

<u>APLHGR Constraint</u>

$$T_A(R) : Minimum(1.0 – T_{A,i}(R)) \geq \delta T_A$$

<u>LHGR Constraint</u>

$$T_L(R) : Minimum(1.0 – T_{L,i}(R)) \geq \delta T_L$$

CPR Constraint

$T_C(R) : Minimum(1.0–T_{C,i}(R)) \geq \delta T_C$

where
$T_{X,i}$ = thermal limit ratio for APLHGR (X=A), LHGR (X=L), or CPR (X=C) for bundle i
δT_X = operational allowance for thermal limit ratio

The optimization problem posed above is solved using a simplified form of the dual feasible direction search method(2) for a given exposure point. This method typically finds a local minimum after a few iterations. Imposed on this local minimum search process are the following secondary constraints:

1. freeze shallow position rods to their beginning–of–sequence positions
2. maintain all deep position rods at or above an input limit position
3. minimize the number of shallow position rods
4. minimize the number of intermediate position rods

II.B Global Optimum

Global optimum is defined as an optimized rod pattern which satisfies all constraints and minimizes the objective function while satisfying all of the constraints at all exposure points within a rod sequence and as a collection of such rod patterns which generates the required cycle energy. Global optimum is typically a compromise between the cycle energy and the the thermal margin requirement. A set of rod patterns may produce the desired cycle energy but may fail to produce the required thermal margin at one or more cycle exposure points. Conversely, a sufficient margin to thermal limits may be achieved by a set of rod patterns with a shortfall of cycle energy or EOC reactivity.

The following global objective is set to monitor the progression to the global optimum:

$$J_G(AO_t, P_t) = \omega_E Min(F_{eoc}(AO_t) - F_{rated}) + \omega_{tm} Min(N_{vtm}(AO_t, P_t))$$

where
ω_x = importance factor for cycle energy (x=E) or thermal margin (tm)
F_x = core flow requirement at EOC (x=eoc) or rated core flow (x=rated)
N_{vtm} = number of exposure points which violate the thermal margin constraints

II.B.1 Axial Optimization

Axial power distribution has a strong influence on the cycle energy as well as on the LHGR and the APLHGR margins. The initial input target axial power offset (index for axial power asymmetry) trend for the entire cycle may be changed to a new target trend depending on the outcome of the global objective. The new axial power offset trend is estimated based on the knowledge based rules described below in Section II.C.

II.B.2 Radial Optimization

Target radial power distribution is chosen based on the consideration of EOC or near EOC thermal margin. The specific goal of radial optimization is to make the radial power distribution as flat as possible in the interior zone of the reactor. This results in uniform burn of fuel bundles, which in turn results in an EOC radial power distribution satisfying thermal margin constraints with minimal or no control blade intervention.

One strategy is to force those dominantly reactive fuel bundles to share a flat power distribution among them. This strategy is suitable for a single fresh batch loading whose bundles are found in the interior zone of the reactor. This strategy works well for core loading patterns at preliminary development stage. In this case, the loading patterns typically contain several problem spots which exceed thermal limits at or near EOC. Because the problem spots consist of dominantly reactive fuel bundles, they need to be forced to share power with other equally reactive fuel bundles during early part of the cycle burn. As the core loading pattern becomes refined, the problem spot may be reduced to a few. The focus should shift from multiple bundle power sharing to core maximum peaking factor reduction.

Another strategy is to make the controlled power distribution stay as close as possible to an equilibrium power distribution. Depending on the requirement from the core loading pattern and other constraints, there can be different choices of equilibrium power distributions. A frequently utilized choice(4) is the Haling power distribution which assumes a single power distribution extending from BOC to EOC. A similar choice is a cycle exposure dependent all rods–out (ARO) power distribution. The Haling power distribution is used when the cycle licensing analysis is based on a Haling cycle depletion. The cycle exposure dependent ARO power distribution is useful when it is exceedingly flat (low radial power peaking factor). Thus the choice of the radial optimization is dependent on the operating strategy and the cycle length of a specific plant.

II.C Knowledge Based Rules

Knowledge based rules (KBRs) were established based on the extensive experience of BWR fuel cycle design available within Framatome ANP. KBRs serve the following purpose:
1. to determine initial rod patterns
2. to rescue MSE from any local minimum trap and to satisfy the secondary constraints
3. to determine improved target axial power offset trend

The initial rod pattern is determined to achieve a gross control of the core reactivity and the radial power peaking. Control blades are fully inserted into selected locations resulting in a high control density core. No consideration is given to the axial power control at this stage.

Rescuing MSE from a local minimum trap starts from detecting the occurrence of being trapped. When MSE reached a local minimum trap, it generates a rod pattern with minor or no difference from one of the previously considered rod patterns. Once it is detected, the escape path is established into the direction that brings the largest impact on the core region with the maximum violation of thermal limit.

The target axial power offset trend is changed by adjusting the axial offset value at both ends of a cycle and adjusting the middle point values in a proportionate manner. The target axial offset is a relatively loose constraint which does not need to and usually can not be satisfied to a tight convergence.

II.D Solution of Local Optimum Problem

Given an initial rod pattern or a previous rod pattern, an improved rod pattern is determined using the dual feasible direction search method:

$$R^n = R^m + \sigma^n P^n$$

where
R^n = rod pattern at iteration n
σ^n = step size
P^n = direction vector at iteration n

The direction vector is determined from the dual feasible direction search method:

$$P^n = \eta^n \nabla J^{(R^m}) + u^n \nabla g(R^m)$$

where
$g(R^m)$ = collection of constraints evaluated with rod pattern from iteration m
η^n, u^n = coefficients of direction vector

The coefficients of direction vector are a solution of the following quadratic programming problem:

$$Minimize \, \| \eta^n \nabla J(R^m) + u^n \nabla g(R^m) \|^2 - u^n g(R^m)$$

$$\eta^n + e u^n = 1$$

where e is a vector of ones. The solution to this problem is easily found using any available quadratic programming method.

II.E Solution of Global Optimum Problem

The solution to the global optimum problem is found using the same dual feasible direction search method. Here the control parameter is the axial power offset vector over the exposure points of a given fuel cycle. Usually a fully developed loading pattern results in convergence after the first cycle step–through. A loading pattern near optimum may require a few global optimization iterations.

III. Results

A computer program named KAMROD was developed based on the methodology presented above with an interface to the MICROBURN–B2 3–D BWR core simulator.(3) KAMROD determines an optimum rod pattern for a single exposure point or for an entire fuel cycle for a given loading pattern. For an 18 month fuel cycle with 3000 MWd/MTU rod sequence exchange interval, about 15 exposure points are considered with an average exposure interval of 1000 MWd/MTU. There are 5 sequence exchanges with exposure interval of 3000 MWd/MTU. For this case, KAMROD takes about 2 hours of CPU time on HP9000 workstation (500 Mhz CPU) for the entire cycle rod patterns. A 24 month cycle rod pattern takes a proportionately more computing time. Experience of KAMROD test runs indicates that its result matches or exceeds in quality the most experienced manual rod pattern design.

Typical results of KAMROD calculations can be examined in various aspects. For instance, consider a local minimum trap encountered during an MSE iteration shown in Figure 1. The MSE iteration converges to a local minimum at iteration 7, which is manifested by the appearance of nearly identical rod pattern at iteration 9. The APLHGR margin constraint is still not satisfied (MAPRAT=0.935 > target=0.910). KBR detects this trap and determines a shallow rod insertion to the notch 34, which results in the satisfaction of all constraints.

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ROD PATTERN AT ITERATION 0
 48.0  48.0  48.0  48.0  48.0  48.0  48.0  48.0
 48.0  48.0   6.0  48.0   6.0  48.0  48.0  48.0
 48.0  48.0  48.0  48.0  48.0  48.0  48.0  48.0
  6.0  48.0   6.0  48.0  48.0  48.0  48.0  48.0
 48.0  48.0  48.0  48.0  48.0  48.0  48.0
 48.0  48.0   6.0  48.0  48.0  48.0  48.0
 48.0  48.0  48.0  48.0  48.0  48.0
 48.0  48.0  48.0  48.0

ROD_PATTERN AT ITERATION 7
 48.0  48.0  48.0  48.0  48.0  48.0  48.0  48.0
 32.0  48.0   8.0  48.0   8.0  48.0  48.0  48.0
 48.0  48.0  48.0  48.0  48.0  48.0  48.0  48.0
  6.0  48.0   8.0  48.0  26.0  48.0  48.0  48.0
 48.0  48.0  48.0  48.0  48.0  48.0  48.0
 36.0  48.0   8.0  48.0  40.0  48.0  48.0
 48.0  48.0  48.0  48.0  48.0  48.0
 48.0  48.0  48.0  48.0
  FLOW  (%)=   92.46  TARGET FLOW  (%)=   90.00
  MAPRAT= 0.935  MFDLRX= 0.900  MFLCPR= 0.869
  NUMBER OF CONSTRAINTS UNSATISFIED   2

ROD_PATTERN AT ITERATION 9
 48.0  48.0  48.0  48.0  48.0  48.0  48.0  48.0
 32.0  48.0   8.0  48.0   8.0  48.0  48.0  48.0
 48.0  48.0  48.0  48.0  48.0  48.0  48.0  48.0
  6.0  48.0   8.0  48.0  24.0  48.0  48.0  48.0
 48.0  48.0  48.0  48.0  48.0  48.0  48.0
 36.0  48.0  10.0  48.0  40.0  48.0  48.0
 48.0  48.0  48.0  48.0  48.0  48.0
 48.0  48.0  48.0  48.0
  FLOW  (%)=   91.29  TARGET FLOW  (%)=   90.00
  MAPRAT= 0.934  MFDLRX= 0.899  MFLCPR= 0.876
  NUMBER OF CONSTRAINTS UNSATISFIED   2

ROD_PATTERN RESCUED FROM LOCAL MINIMUM TRAP
 48.0  48.0  48.0  48.0  48.0  48.0  48.0  48.0
 32.0  48.0   8.0  48.0   8.0  48.0  34.0  48.0
 48.0  48.0  48.0  48.0  48.0  48.0  48.0  48.0
 10.0  48.0   8.0  48.0  24.0  48.0  48.0  48.0
 48.0  48.0  48.0  48.0  48.0  48.0  48.0
 36.0  48.0  10.0  48.0  40.0  48.0  48.0
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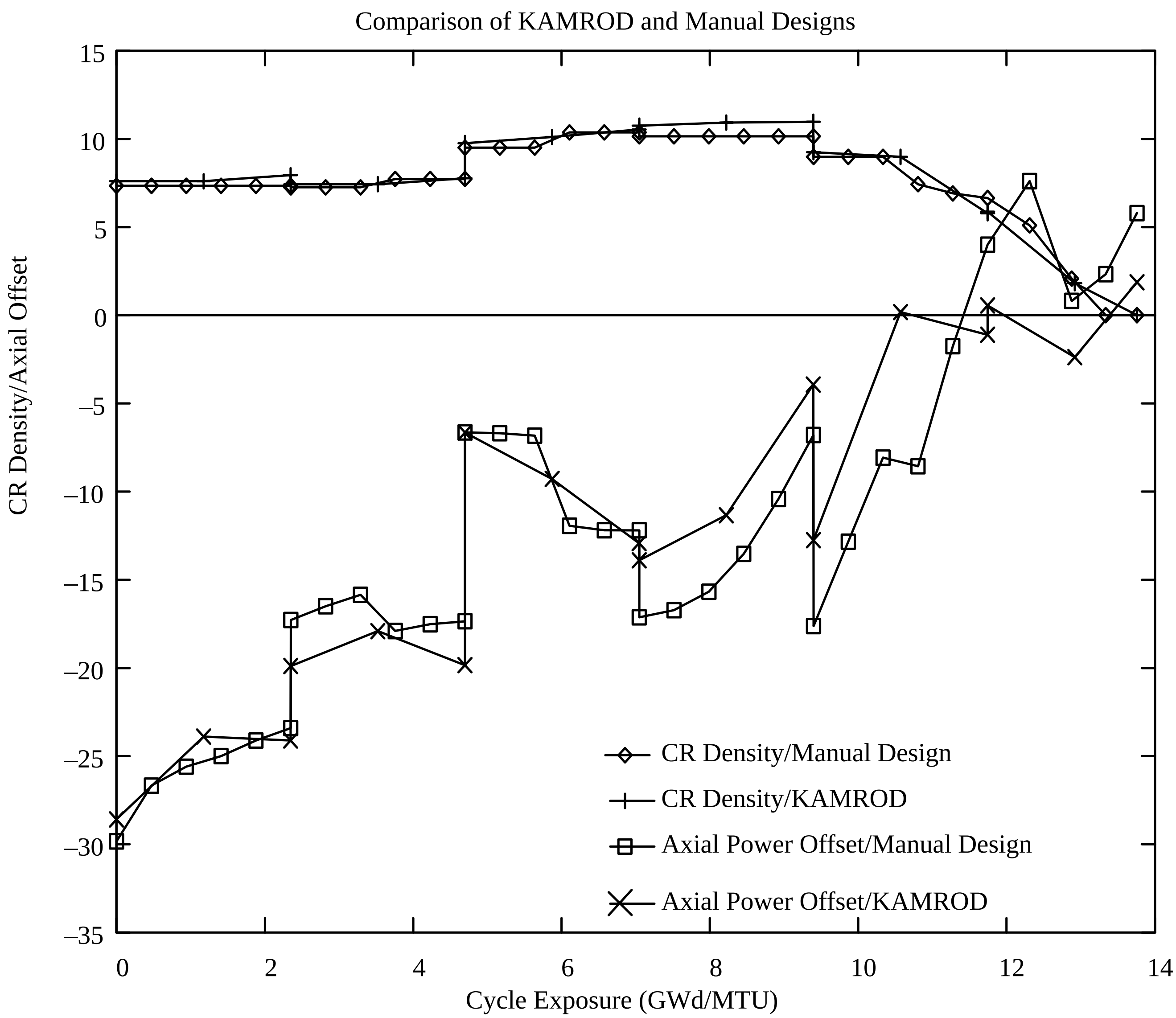
48.0  48.0  48.0  48.0  48.0  48.0
48.0  48.0  48.0  48.0
 FLOW  (%)=   90.18  TARGET FLOW  (%)=   90.00
 MAPRAT= 0.891  MFDLRX= 0.879  MFLCPR= 0.893
 NUMBER OF CONSTRAINTS UNSATISFIED   0
```

Figure 1. Rescue of Mathematical Search from a Local Minimum Trap

Another sample result to be examined is a comparison of a whole cycle rod pattern design shown in Figure 2. Here the control rod (CR) density and the axial power offset trends are compared between a manual design and the corresponding KAMROD design. There is a remarkable similarity in trends of the two calculated parameter. This indicates a KAMROD design meets requirements of an RRS cycle.



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