OPERATING STRATEGY GENERATOR METHOD AND UTILIZATION IN POWERTRAX™ PWR CORE MONITORING SYSTEM*

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ABSTRACT

An operating strategy generator for a PWR refers to a tool which provides guidance for operators as to operating actions to be taken to achieve certain maneuver of reactor power in an efficient way. To generate a useful operating strategy, an accurate projection of the reactor behavior has to be made in order to satisfy the plant technical specification limits on fuels and the capacity of plant chemical systems. This leads to the use of a full scope core physics design method for making the projection. The Siemens PWR core monitoring system POWERTRAX™ contains an optimum operating strategy generator that satisfies such a requirement. The accuracy of the projection and the usefulness of the generated guidelines were validated by comparing the proposed operating strategy with the actual operating practices employed by experienced operators for some selected power transients.

1. INTRODUCTION

An operating strategy generator for a PWR refers to a tool which provides operators with guidances on operating actions to achieve an efficient maneuver of reactor under normal operating conditions including load follow, startup, and shutdown. To generate a useful operating strategy which will satisfy plant technical specification limits and the capacity of a plant chemical system when applied to the actual operation, an accurate projection of the reactor behavior has to be made. This consideration leads to the use of a full scope design method for making the projection. The Siemens core monitoring system POWERTRAX™[1] contains an operating strategy generator that satisfies such a requirement. This system has been in use for over four operational cycles in the H. B. Robinson and the Shearon Harris PWRs. This paper presents the method and the validation of the operating strategy generator implemented in the POWERTRAX™ system.

2. DESIGN OF OPERATING STRATEGY GENERATOR

The operating strategy generator (abbreviated as OSG) in the POWERTRAX™ system is intended to work for those PWRs utilizing the axial flux difference as the main monitored parameter for power distribution control. The POWERTRAX™ OSG determines an optimized strategy of operating PWRs to meet the

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required power demand schedule based on a multistage optimization process (MOP). The major purpose of adopting a MOP is to detach the system state equations from the optimization method so that the optimization method does not govern the characteristics of the state equations. The complex, non–linear nature of the state equations representing the reactor behavior is handled by a full scope design purpose core simulator.

The POWERTRAX™ OSG permits the optimal target to be either the core stability against the xenon–induced spatial power oscillation or the minimization of radioactive waste water processing or a combination of both. Although these two targets constitute a conflicting goal, the POWERTRAX™ OSG determines a compromised solution through a procedure of multiple control parameter criticality search and multi stage axial power difference control. The POWERTRAX™ OSG demands only basic input data from users such as the power demand schedule and constraints on the control parameters and the system state parameters.

The system dynamics model employed by the POWERTRAX™ OSG is the MICROBURN–P(2) or the PRISM PWR core simulator.(3) This model includes a two group three–dimensional steady state neutron diffusion equation, steady state fuel temperature and moderator density equation, and transient Xe–135 and Sm–149 depletion equations. Because the transients to be simulated by POWERTRAX™ OSG involves only normal operational transients (slow transients), there is no need to consider the kinetics form of the neutron diffusion equation or the thermal–hydraulic equation. Also included in the model is a reactivity control model utilizing control rods and soluble boron. Auxiliary controls such as reactor power and inlet temperature can also be used as a part of the control model.

3. OBJECTIVE FUNCTIONAL AND CONSTRAINTS

The objective of the POWERTRAX™ OSG is to generate a control sequence that will meet the input power demand schedule. Whether a specific operating strategy is working as predicted must be verifiable during the actual operation. This is because the POWERTRAX™ OSG is not a control system but rather a guidance system which supports the operator who is in charge of the actual control. Thus, an operator should be able to follow the guidance easily and alter the course if a need arises. In the latter case, the operator may revise the power demand schedule and regenerate the operating strategy on the fly. This consideration leads to an objective functional based on the continuously monitored parameters:

$$J(u) = \int \left[W_P |P(u(t)) - P_d(t)| + W_A |A_f(u(t)) - A_{fd}(t)| \right] dt \tag{1}$$

where W_P and W_A are adjoint coefficients that satisfy the normalization constraint, i.e.,

$$W_P + W_A = 1 \tag{2}$$

and,

$P(u(t))$ = actual power at time t

$P_d(t)$ = power demand at time t

$u(t)$ = control strength vector at time t

$A_f(u(t))$ = actual axial flux difference at time t

$A_{fd}(t)$ = desired axial flux difference at time t

This objective functional represents an active control of axial power distribution as it involves the axial flux difference (AFD) target. The control vector $u(t)$ is a linear combination of control parameters:

$$u(t) = w_R(t)u_R(t) + w_B(t)u_B(t) + w_T(t)u_T(t) \tag{3}$$

where the adjoint coefficients are subject to the normalization condition,

$$w_R(t) + w_B(t) + w_T(t) = 1 \tag{4}$$

and

$u_R(t)$ = control strength taken by control rod at time t

$u_B(t)$ = control strength taken by soluble boron at time t

$u_T(t)$ = control strength taken by inlet temperature at time t

Furthermore, the control rod strength vector $u_R(t)$ is a union of individual control bank vectors:

$$R(t) = \{r|(R_1(t), R_2(t), \ldots, R_N(t)), R_n^{\min} \le R_n(t) \le R_n^{\max}\} \tag{5}$$

The constraints are mostly derived from the limiting conditions on normal operation:
<u>control rod insertion/withdrawal limit</u>

$$R^{\min} \le R(t) \le R^{\max} \tag{6}$$

<u>control rod overlap insertion</u>

$$R_n(t) = R_{n-1}(t) + \Delta R(R_{n-1}(t)) \tag{7}$$

<u>soluble boron boration/dilution rate limit</u>

$$\dot{B}^{\min}(B(t_i)) \le \dot{B}(t)|_{t=t_i} \le \dot{B}^{\max}(B(t_i)) \tag{8}$$

<u>axial flux difference limit</u>

$$A_f^{\min}(P_d(t_i)) \le A_f(u(t)) \le A_f^{\max}(P_d(t_i)) \tag{9}$$

<u>inlet temperature constraint</u>

$$T^{\min} \le T(t) \le T^{\max} \tag{10}$$

4. TRANSFORMATION OF OBJECTIVE FUNCTIONAL

The reactor power is maintained by keeping the reactor critical at a given thermal condition. Thus the core power is alternatively represented as the core criticality eigenvalue by a core simulator, which leads to the following modified form of the objective functional:

$$J(u) = \int \left[W_K |K(u(t)) - K_d| + W_A |A_f(u(t)) - A_{fd}(t)| \right] dt \tag{11}$$

where

$K(u(t))$ = actual eigenvalue at time t

K_d = desired eigenvalue

The time discretized form of the above equation is,

$$J(u) = \sum_{i=0}^{I} \left[W_K |K(u_i) - K_d| + W_A |A_f(u_i) - A_{fd}(t_i)| \right] \tag{12}$$

In the actual power maneuver, the reactor alternates through a period of rapid power level change and another period of power level plateau with a relatively large change in power distribution. During the rapid power level change, the primary objective is to meet the power demand while maintaining the power distribution within the limiting condition (Eq. (9)). The conditioning of power or xenon distribution should take place in a leisurely manner during the constant power level period. This consideration leads to the following approximate form of the objective functional:

$$J(u) = J_s(u) + J_c(u) \tag{13}$$

$$J_s(u) = \sum_{i=0, \dot{P}_i > \alpha_p}^{I} |K(u_i) - K_d| \tag{14}$$

$$J_c(u) = \sum_{i=0, \dot{P}_i \le \alpha_p}^{I} \left[W_K |K(u_i) - K_d| + W_A |A_f(u_i) - A_{fd}(t_i)| \right] \tag{15}$$

where

α_p = a threshold power change rate separating the rapid power change period from the power plateau period

5. PRINCIPLE OF STABILITY

The control problem defined above represents a loosely coupled control system which can be solved by iterating between the core simulator and the minimization of the objective functional. The iteration should be executed at each discrete point in time marching from the initial state in order to make the optimization process feasible. The success of this approach depends on the satisfaction of the requirement that each of the multistage optimization process (MOP) should be optimized in such a way that its result should not damage the optimization of any future stage. Many previous approaches tried to adopt a mathematical optimization method that invariably required a simplification of the state equations.(4) A practical solution to this problem is found here by developing and proving a lemma called ”principle of stability”.

The principle of stability is posed as follows:
”A steady state is a stable state wherein state variables are in equilibrium with each other. Therefore, a non–steady state can be made stable if state variables can be repeatedly brought into a condition characteristic of the steady state.”

The proof of this lemma is obtained by considering a characteristic condition of a steady state. Suppose that a steady state condition is represented by two distinctive state parameters having the same normalized distribution:

$$A_0(\underline{r}) = B_0(\underline{r}) \tag{16}$$

The disturbed distribution of the parameter B can be represented in terms of the first order Taylor series expansion, i.e.,

$$B(\underline{r}) = B_0(\underline{r}) + \frac{\partial B}{\partial A}[A(\underline{r}) - A_0(\underline{r})] \tag{17}$$

Following the lemma, the disturbed distribution of the parameter B is now set equal to the disturbed distribution of the parameter A (a condition characteristic of the steady state). The above equation can be rearranged as follows:

$$\left(1 - \frac{\partial B}{\partial A}\right)A(\underline{r}) = B_0(\underline{r}) - \frac{\partial B}{\partial A}A_0(\underline{r}) = \left(1 - \frac{\partial B}{\partial A}\right)A_0(\underline{r}) \tag{18}$$

Because the two parameters are distinctive (otherwise, we have only one parameter), the partial derivative term is in general not equal to 1. Thus, we obtain,

$$A(\underline{r}) = A_0(\underline{r}) \tag{19}$$

Vice–versa, by eliminating the parameter A in favor of B, we obtain,

$$B(\underline{r}) = B_0(\underline{r}) \tag{20}$$

What this means is that the steady state is re–established by subjecting the perturbed parameters to a condition (A=B) characteristic of the steady state. Thus, the lemma is proven.

The principle of stability is a convenient and powerful guideline for determining control actions at discrete time points in the forward marching solution of the optimization problem. The power distribution control needed to avoid any future xenon–induced power oscillation can be found in this principle.

6. MULTIPLE CONTROL CRITICALITY

The minimization of the functional given by Eq. (14) is equivalent to finding an optimal control, $\hat{u}_i$, that satisfies,

$$K(\hat{u}_i) = K_d \tag{21}$$

$$\hat{u}_i = \hat{w}_R(t_i)\hat{u}_R(t_i) + \hat{w}_B(t_i)\hat{u}_B(t_i) + \hat{w}_T(t_i)\hat{u}_T(t_i) \tag{22}$$

$$\hat{w}_R(t_i) + \hat{w}_B(t_i) + \hat{w}_T(t_i) = 1 \tag{23}$$

for the time points which satisfy,

$$\dot{P}_i > \alpha_p \tag{24}$$

A non–trivial solution for this problem is found by prioritizing each control action. During the rapid power level change dictated by Eq. (24), the primary control that produces such a rapid change in power is the control rod. Thus, the control parameters are prioritized by setting,

$$\hat{w}_R = 1 - \epsilon_B - \epsilon_T \tag{25}$$

$$\hat{w}_B = \epsilon_B \tag{26}$$

$$\hat{w}_T = \epsilon_T \tag{27}$$

where $0 \le \epsilon_B < \epsilon < 1$ and $0 \le \epsilon_T < \epsilon < 1$.

Eq. (21) is a typical criticality search problem . The remaining equations simply represent multiple controls prioritized according to the control system characteristics. For this reason, the solution for the optimal control of the reactor during a rapid power level change is called a multiple control criticality (MCC). Since the MCC problem is well posed, its solution is easily found by an iteration method.

7. POWER DISTRIBUTION CONTROL

The solution of the control problem defined by the second objective functional, Eq. (15), provides an optimal power distribution control. Realizing that the sensitivity of AFD to a change in boron or an inlet temperature is negligible, the minimization of this functional results in,

$$\frac{\partial J_c(u)}{\partial B} = \sum_{i=0,\dot{P}_i \le \alpha_p}^{I} \frac{\partial |K(u_i) - K_d|}{\partial B} = 0 \tag{28}$$

$$\frac{\partial J_c(u)}{\partial T} = \sum_{i=0,\dot{P}_i \le \alpha_p}^{I} \frac{\partial |K(u_i) – K_d|}{\partial T} = 0 \tag{29}$$

$$\frac{\partial J_c(u)}{\partial R} = \sum_{i=0,\dot{P}_i \le \alpha_p}^{I} \left[W_K \frac{\partial |K(u_i) - K_d|}{\partial R} + W_A \frac{\partial |A_f(u_i) - A_{fd}(t_i)|}{\partial R} \right] = 0 \tag{30}$$

Eq. (28) and Eq. (29) are a simple criticality search problem. Eq. (30) represents the consequence of a control rod movement, namely the simultaneous shift of eigenvalue and AFD. The adjoint coefficient of the reactor eigenvalue is now defined as,

$$w_k = \frac{\partial \Delta R}{\partial B} \tag{31}$$

This definition merely expresses that the eigenvalue shift caused by the control rod movement may be compensated by the boron change. Eq. (28) through Eq. (31) and the additional requirement,

$$w_k + w_A = 1 \tag{32}$$

are the five equations needed to determine the five unknowns, B, T, R, w_k, and w_A at any give time point t_i. This is a well posed problem which can be solved by an iteration method. POWERTRAX™ OSG utilizes the Newton–Raphson method.

The optimality of the power distribution control solution is dependent on the definition of the desired axial power difference, $A_{fd}(t_i)$. The principle of stability requires that another state variable having the same distribution (axial difference) as the axial power distribution (AFD) needs to be identified. This parameter does not need to be a monitored (measured) parameter. It can be any one of the many feedback variables available in a core simulator which provides the desired characteristics of the steady state. Suppose one such parameter is identified and its axial difference is designated as Q(t). Then the desired AFD at any time is defined as follows:

$$A_{fd}(t_i) = Q(t_i) \tag{33}$$

The power distribution control now works as follows:
1. At each time point t_i, the desired axial power difference, $A_{fd}(t_i)$, is set to $Q(t_i)$.
2. A control rod position which generates the desired axial power difference is found by solving Eq. (30).
3. The core criticality is maintained by solving Eq. (28) (boron search) and Eq. (29) (inlet temperature search).
4. State variables (neutron flux, power, coolant density, xenon, and etc) are determined when the control rod position search of Step 2 is converged.
5. Time is advanced to the next point (t_{i+1}) and the Step 1 through 4 is repeated.

8. RESULTS

The POWERTRAX™ OSG is currently being used in H. B. Robinson and Shearon Harris PWRs. The method was initially verified by simulating many past operational transients in these two reactors for which measured values of control parameters are available. These actual transients were initiated by careful planning and executed by experienced operators. Thus, they represent experience based control practices which provide a benchmark basis for testing the practicality and the optimality of the operating strategy produced by the POWERTRAX™ OSG.

8.1 POWER DEMAND VARIATION A

An example of the planned power transients is shown in Figure 1. Here, the actual history of power change, control bank D maneuver, and boron PPM change made during the power transient are presented. The variation of the power level starts from 100 % of the full power and reaches about 45 % power in about 5 hours. The reactor then stays at the low power level for about 52 hours and then goes back to the full power in about 7 hours. This type of load variation occurs during a load follow operation. Taking the actual power history data for the power demand schedule, an operating strategy is generated using the POWERTRAX™ OSG. The resulting control bank position, soluble boron, and axial flux difference (AFD) data are compared with the core follow simulation result.

Figure 1 shows that the POWERTRAX™ OSG generated control bank position goes somewhat deeper than the actual bank position for the latter half of the low power plateau. This rod maneuver and the slightly deeper position at the return to the full power are the result of the optimum operating strategy. One benefit of this strategy is a reduction of 40 PPM on the peak boron demand compared to the actual boron demand. Also, the axial flux difference indicates that the POWERTRAX™ OSG generated operating sequence produces a significantly smaller AFD swing than the actual operation. Finally, the return to the equilibrium (stable) condition AFD is much quicker than the actual operation.

8.2 POWER DEMAND VARIATION B

Another example is shown in Figure 2. The power demand schedule in this example requires that the reactor be brought down to the 15 % power level in about three hours and starts a return to the full power after 12 hours of low power operation. This type of load variation occurs when a periodic system test or repair is performed. POWERTRAX™ OSG was run for this power demand schedule and the resulting control bank position, soluble boron, and axial flux difference (AFD) data were compared with the core follow simulation result.

Figure 2 shows that the POWERTRAX™ OSG generated control bank position is significantly simpler than the actual operation especially during the latter half of the low power operation. The peak boron demand is about 10 PPM less than the actual demand while the overall boron trend resembles the actual boron trend. The axial flux difference trend indicates that the POWERTRAX™ OSG generated operating sequence produces a significantly smaller AFD swing during the latter half of the low power plateau than the actual operation. Also the equilibrium (stable) AFD is recovered faster than the actual operation.

8.3 PRACTICALITY OF POWERTRAX™ OSG

The operating strategy generated by POWERTRAX™ OSG is directly translated into guidelines on operator actions for changing control parameters (control bank position, boron concentration, inlet temperature) at each time point. The trend of control parameters generated by POWERTRAX™ OSG is similar to the trend of control actions taken by experienced operators. This means that the operating strategy generated by POWERTRAX™ OSG is practical and within the context of current operating practices.

The computing time needed for generating an optimal control sequence described in each of these two examples is about 1.5 times the amount needed for running a core follow calculation for the same power schedule using the full scope 3–D design code of POWERTRAX™. Thus, the POWERTRAX™ OSG is a practical method that can be employed by operators before or during the planned power transient. Indeed, this is how the POWERTRAX™ OSG has been used in the two PWR plants.

CONCLUSION

The optimal control method, POWERTRAX™ OSG, is capable of generating an optimal control sequence in a practical manner utilizing a full scope 3–D core simulator. The resulting optimal control sequence can be directly used to safely and economically execute a planned power maneuver. Test cases, two of them quoted in this paper, indicate that a control sequence generated by this method provides a stable power distribution, thus significantly reducing any potential AFD swing due to ensuing xenon transients, and a reduction in boron system demand compared to the actual operation performed for the same power demand schedules. Thus, the benefit achieved by the optimal control sequence produced by the POWERTRAX™ OSG is a reduced thermal load fluctuation in fuel rods and a reduced amount of radioactive effluent treatment for PWR operations involving weekend power reduction, power reduction for testing system components, and a general load follow operation.

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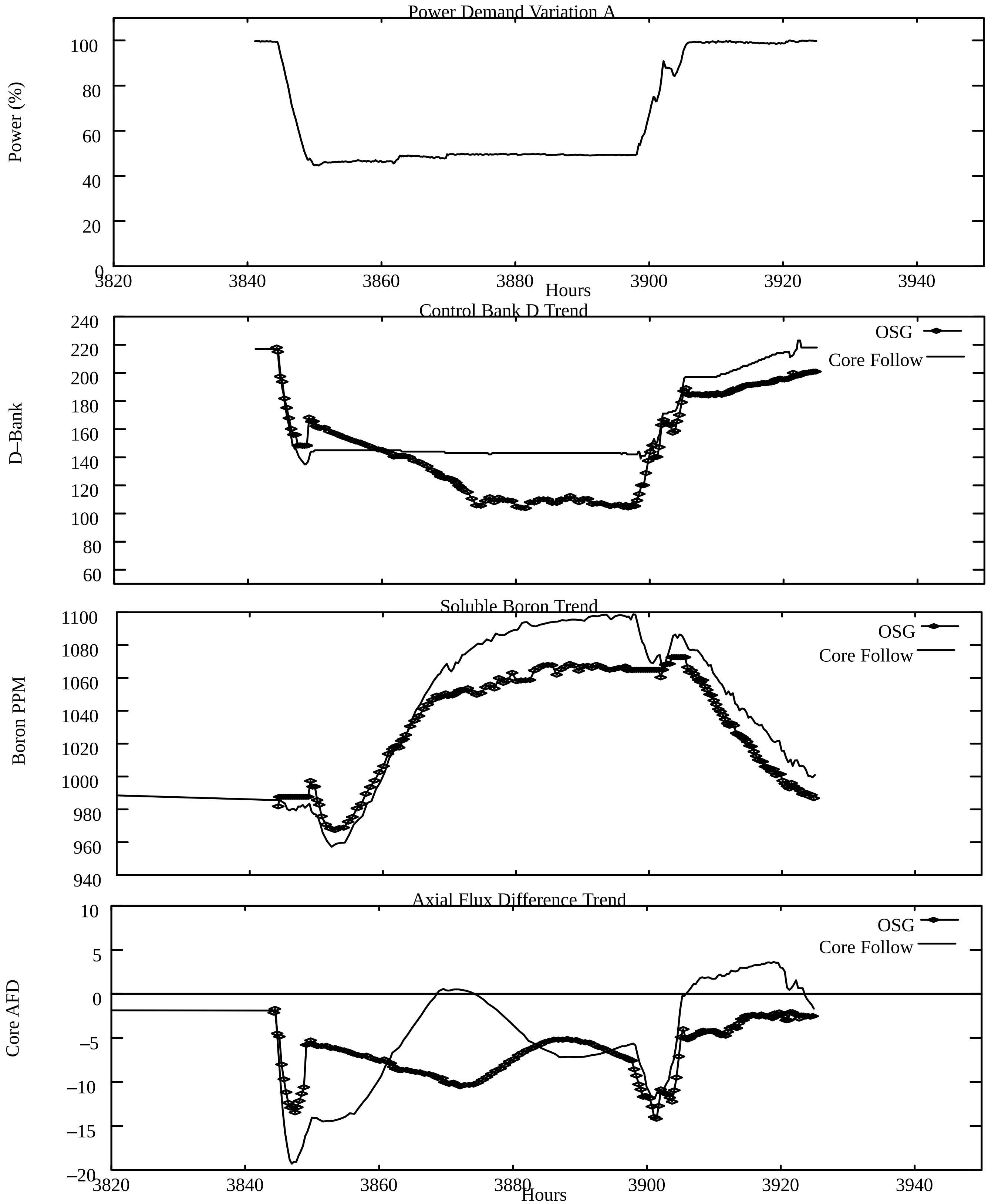

Figure 1 OSG Generated Operating Strategy Versus Actual Operation, Example 1

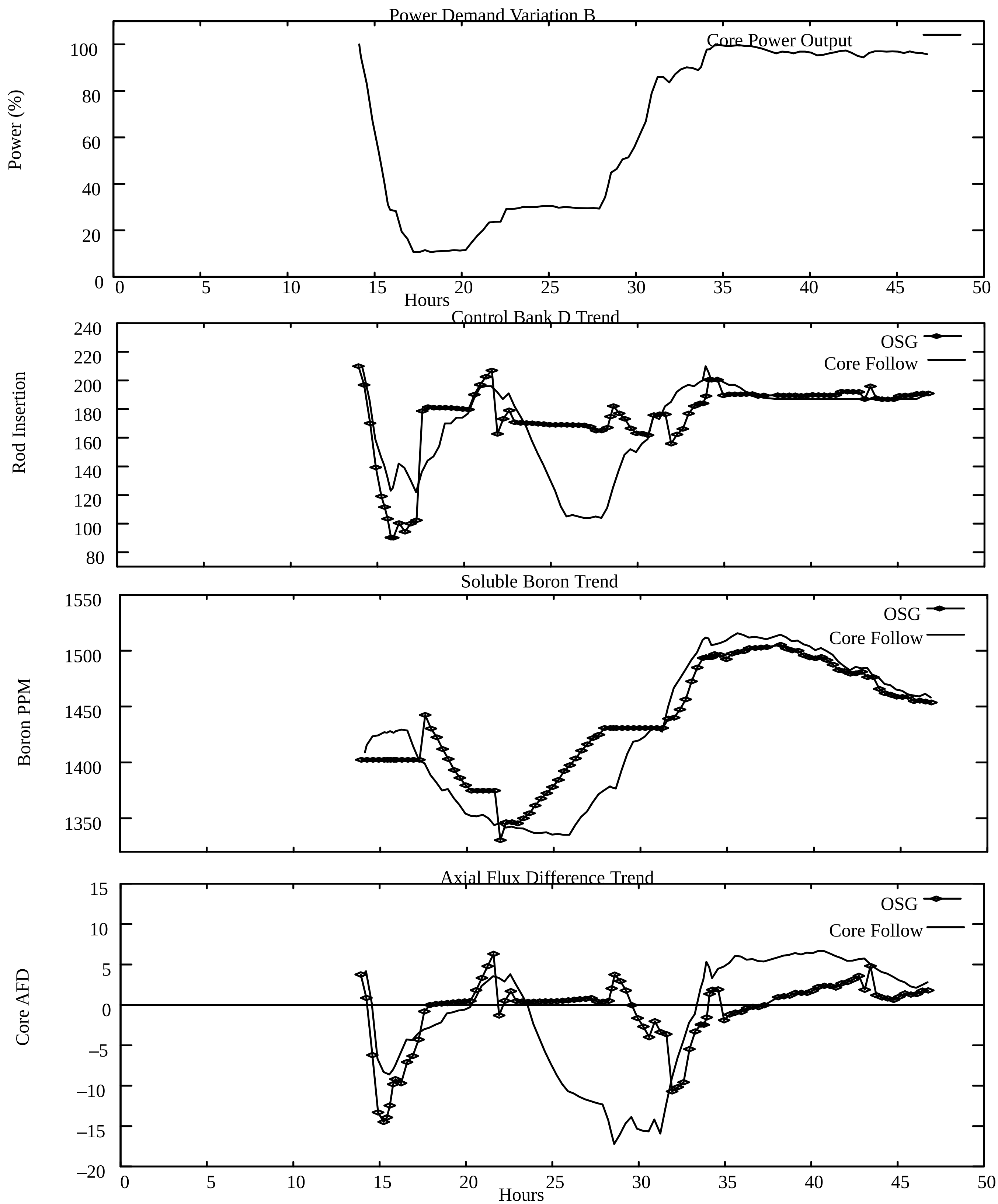

Figure 2 OSG Generated Operating Strategy Versus Actual Operation, Example 2