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Evaluation of the Load Follow Operation Capability of KNGR using SAF Simulator

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Abstract

The load following capability of KNGR is evaluated for both daily load follow and general grid follow operations using the SAF simulator which is the new FRAMATOME simulator. All the main KNGR systems that could impact the behavior of Mode K or that can be directly impacted by the Mode K have been modelized in the SAF. Ten load follow transient have been simulated in order to cover the KNGR performance requirement as regards the load following operation. The types of load following operation considered are the scheduled daily load follow transient with and without frequency control operation, the weekend operation and the fast return to power operation.

1. Introduction

KNGR (Korean Next Generation Reactor) is an evolutionary PWR rated at 4000 MWth, which is currently under development in Korea[1]. One of the top-tier requirements of KNGR is that it shall be able to do a wide range of load maneuverings[2]. To do this, the Mode K control logic has been originally developed by KAERI[3].

The Mode K control system is designed to provide the reactivity control and the axial power profile control simultaneously and automatically by mainly using the CEAs, with operator control of the soluble boron concentration, during the load maneuvering. It is consisted of two control system. One is average coolant temperature (TAVG) control and the other is axial shape index (ASI) control.

In this paper, the load following capability of KNGR is evaluated for both daily load follow and general grid follow operations using the SAF simulator which is the new FRAMATOME simulator[4]. All the main KNGR systems that could impact the behavior of Mode K or that can be directly impacted by the Mode K have been modelized in the SAF.

The simulations have been defined in one hand, to cover all kinds of load following transients defined in the performance requirements for KNGR, in the other hand, to get the sensitivity of performances to certain parameters such as bank worth or reference overlap. Consequently, multiple simulations have been performed for a same transient with different design parameters and/or set-points. Combining different types of transients and different design parameter values, it has been chosen a total number of 10 simulation cases.

The types of load following operation considered are the scheduled daily load follow operation with (i.e., grid following operation) and without frequency control in operation, weekend operation, and fast return-to-power operation.

2. Design Features of KNGR Load Follow Control

2.1. Mode K characteristics

The main characteristic of the Mode K core control concept is the control of the average temperature (TAVG) and axial power distribution (represented be ASI) simultaneously in an automatic way. The boron concentration variations are performed by the operator following a predetermined pattern of soluble boron concentration versus time determined mainly in order to compensate xenon concentration variation and to keep control banks at positions for which the ASI control is effective[5].

The main task of the average coolant temperature control is to maintain the coolant temperature around the reference value. The TAVG set-point depends on the turbine load index, elaborated from the turbine first stage pressure representative of the thermal power when the turbine by-pass system is closed. The average coolant temperature deviation signal commands the bank movement direction and the bank movement speed. A positive TAVG deviation signal induces bank insertion. A negative TAVG deviation signal induces bank withdrawing. When the TAVG deviation increases, the bank movement speed increases. The speed is one of two discrete rates, low rate of 3 inch/min and high rate of 30 inch/min. The bank movement speed is identical for all the banks.

The purpose of ASI control is to limit axial oscillations of power distribution mainly due to xenon variations consecutive to power variations, in order to increase maneuverability and load follow flexibility. That is obtained by controlling the ASI parameter. The ASI control moves banks in order to bring ASI back to its dead-bank defined around the ASI target value. It moves the most suitable bank considering the bank movement direction, the bank positions into the core and the characteristics behavior resulting from the insertion or withdrawal of control banks.

There are five stages that depend on the ASI deviation value, which are overlap restoring stage, fixed overlap stage (FOS+/-), and ASI restoring stage (ARS+/-).

The coupling between TAVG and ASI controls is based on the following principles.

TAVG control has priority over ASI control and the bank movement direction is defined by the temperature deviation.

The Mode K logic uses the characteristic of the TAVG deviation to determine the movement direction and the speed, the ASI stage flag respresenting the ASI deviation magnitude that indicates the necessity for the ASI controlling, the bank withdrawal positions to determine the bank overlaps and to compare them to the reference overlaps and the bank fictitious positions and to compare them to the top and to the bottom of the core.

2.2. Daily Load Follow and Frequency Control Operation Characteristics

The transients simulated with SAF that are analyzed in this paper are the main load following transients defined in the performance requirements for the KNGR.

A daily load follow transient is a typical scheduled power modulated transient that is performed by the nuclear power plant. Within 24 hour period, turbine power is decreased for a few hours to a part power level and then brought back to full power. The magnitude of the power variation is at least 50% of rated power. The load variation rate is at least 25%/hr. In the frame of the daily load follow operation, the duration of the operation with stabilized set-point at intermediate power levels can vary between 4 and 10 hours. The daily load follow operation shall be performed until up to 90% of the cycle length for every fuel reload cycle. The typical daily load follow transient is 100-50-100% NP, 14-2-6-2 hr.

The grid follow operation corresponds to the plant operation under frequency control. There are two kinds of frequency controls, the local frequency control and the remote frequency control.

Local frequency control performs automatic actions as soon as there is an imbalance between the electricity power production and demand which leads to deviate the frequency from its reference value. The controller gain is such that a 20 mHz drop in frequency will produce an increase in power demand of 1% of rated power. The normal range for power variations induced by this control is ±2.5%.

The magnitude of the remote frequency control demand signal is generated at the national dispatching center in real time. It accounts for both the integral of the frequency deviation value versus time and the exchanged power deviation from the scheduled exchanged program with other countries for example the load signal variation speed is below 2%/min. The maximum power variation magnitude of the signal is ±10% when power level is above 50% and it is reduced to ±2% when power level is under 50% of nominal power.

2.3. Simulator Characteristics

Mode K load follow transients are performed with the SAF simulator.

This simulator is mainly used for operator training, in normal and accidental conditions, as well as for validating modifications before implementation on site. It can be used also to investigate the creation of new models, to validate human factor studies, to optimize the control room, to check disposition considered during emergency states and to evaluate accident consequences in best-estimate conditions.

The calculational code used to simulate the reactor coolant system is the code TRACAS. TRACAS is a node and junction two-phase model. It is a five-equation code. 2 mass balance equations (two phases per volume), 2 energy balance equations (two phases), and 1 momentum equation (on junctions). TRACAS uses 54 nodes and 58 internal junctions. It has been qualified by comparison with design codes FRACAS, THEMIS and RELAP.

The neutronic model COR is an axial model based on the FRAMATOME one dimensional neutronic design code ESPADON. The two codes use the same neutronic models. COR is a 1D diffusion model with two energy groups. It handles core axial geometry with 20 mesh points. It includes the treatment of all feedback effects of water temperature, Doppler and xenon. Control rods are simulated by poison added in each mesh. The mesh where a rod is partially inserted is treated by a weighting taking into account the flux distribution within the mesh.

The core model uses the boron concentration value and the axial temperature distribution provided by TRACAS and the rod bank positions provided by the Mode K RRS to calculate the average flux versus reactivity, the flux axial distribution resolving the diffusion equation in steady state, the core reactivity, the xenon and iodine concentration variation, and the cross sections considering the current operating conditions (i.e., moderator density, boron concentration, fuel temperature), xenon and iodine concentrations.

3. Simulated Cases and Their Characteristics

The simulations have been defined in one hand, to cover all kinds of load following transients defined in the performance requirements for KNGR, in the other hand, to get the sensitivity of performances to certain parameters such as bank worth or reference overlap. Consequently, multiple simulations have been performed for a same transient with different design parameters and/or set-points. Combining different types of transients and different design parameter values, it has been chosen a total number of 10 simulation cases. Table 1 summarizes simulated case characteristics.

In Figure 1 is shown the load variation pattern of 14-2-6-2 hr, 100-50-100% operation for the daily load following operation. A ramp rate of 6 MWe/min, which is equivalent to 25%/hr, is chosen in the SAF.

In Figure 2 is shown the load variation pattern of 14-2-30-2 hr, 100-50-100% operation for the weekend load following operation. During the later time period at part load, it is expected that rather large positive reactivity due to Xe decay is compensated.

In Figure 3 is shown the load variation pattern simulated. The average reference power levels are 62% at part load and 89% at full load, and the ramp rate is set to 4 MWe/min with which it takes about 95 minutes to change the power level by 27%. The load variations for the frequency control are superposed on this scheduled daily pattern. The pattern of load variations is same to that in the typical set, but the magnitude was exaggerated up to ±10%, for the remote frequency control. In addition, variations within ± 2.5% range were accommodated for the local control.

In Figure 4 is shown the load variation pattern of the fast return-to-power operation transient. At the time when the Xe reactivity starts to decrease at part load (6.6 hr), the power level is increased to 100% NP with a ramp rate of 25 MWe/min (1.8%/min). The plant has been operated in the grid following mode before starting the fast ramp-up, but no signal for the frequency control is accommodated thereafter.

Each transient is simulated for 1 day cycle except the weekend operation for which 2 days are necessary. Considering the different core conditions, three fuel burn-up states of the equilibrium cycle were considered. The performance sensitivity of the four following parameters is analysed, ARS+/- set-points, reference overlap, set-point of temperature dead-band for low speed and reactivity worth of banks.

Most of the cases simulate the grid following operation because this operation is regarded as the most challenging to both core and NSSS controllability. The dependency of controllability on each parameter may be distinguished as follows.

Cases 1, 5, and 7 are expected to show the burn-up dependency. Especially in the viewpoint of dilution capability comparing cases 4 and 11 show that, too. With considerations for the higher power defect (higher moderator temperature coefficient), stronger Xe instability, and limited dilution capability near EOC, more cases are simulated at 90% EOC.

Cases 1 and 2 are expected to show the difference in the magnitude of ASI deviation due to different ASI dead-band width. Case 2 allows larger ASI deviation without ASI control actions and may result in a larger perturbation on ASI than case 1.

Cases 5 and 6 will show the ASI deviation depends on the reference overlap. The availability of bank(s) with which the Mode K logic results in better controllability may depend on the reference overlap.

The temperature control has the priority on the ASI control in the current Mode K logic. Therefore the larger the dead-band is, the longer time during no bank moves for ASI controlling is. Cases 7 and 10 will show mainly the difference in the magnitude of ASI deviation while the average temperature is maintained within the dead-band.

In addition to the narrower temperature dead-band, the ASI target is increased of 2.5% in case 10 compared to other cases. Changing the ASI target from the equilibrium ASI (ESI) is one of the possibilities for improving the stability in ASI control. Furthermore, a different boron scenario from case 7 was used for case 10. The starting time of boration after the return-to-power was delayed 50 minutes compared to the scheduled scenario. This delay may result in a deep insertion of P2 bank and better ASI controllability during the remaining period.

Cases 1, 3, 4, cases 7, 9 and cases 8 will show the controllability for each kind of operation.

4. Evaluation of the Capability of Mode K

The simulated results of each case are shown in Figures 5 through 14 for the coolant average temperature deviation and the ASI deviation. The Tables 2 and 3 summarize the main results as regards TAVG deviation, ASI deviation, liquid wastes, number of bank steps, axial power peak increase, and bank insertion limit. The maximum positive and negative ASI deviations are presented, as well as the time period during which ⊿ASI remains out of the control dead-band and the time period during which ⊿ASI remains out of a reasonable dead-band of ±5%.

These tables present between brackets, the potential negative deviations that could occur at the end of transients if there is no adaptation of boration/dilution scenario to control ASI.

The TAVG is controlled correctly in all the transients, whatever the burn-up the transient profile (daily load follow operation, fast return to power or week-end operation) and the set-points (ARS set-point, reference overlap, ASI target value, TAVG dead-band magnitude) are.

When the frequency control signal is superposed to the load follow transient there are high rate bank movement demands from time to time. These demands are due to high power variation rates induced by the frequency control signal. They generate fast large bank movements at high power levels after the return to the maximum power level and consequently induce fast large ASI deviations.

For the ASI control, it is noticed that for all the simulated transients, whatever the burn-up, the set-points (reference overlap value, ARS +/- set-point values, ASI target value, bank worth) and the profile (daily load or grid follow transient, fast return to power transient, week-end operation), an adaptation of the scheduled boron scenario performing a dilution at the end of the transient to insert P2 in order to bring back ASI to its dead-band improves the ASI control. The magnitude of the negative ASI deviations are reduced in a large way. Therefore, ASI is maintained higher than 5%. These dilutions at the end of the transient have been performed in cases 3, 4, 6, 8, and 9. They are not performed in case 1, 2, 5 and 10 because they are not yet necessary since the ASI deviation remains lower than 5%. Nevertheless, if the transient had been continued the dilution would had been performed certainly.

In case of a deviation occurs at the end of the transients it is controlled by the suitable adaptation of the scheduled boron scenario, even if for case 7 transients have been simulated without adapting the boron scenario.

At beginning of life mode K controls ASI correctly for all kind of operations. At middle of the cycle and at 90% of the end of the cycle mode K controls ASI correctly at part load for all kind of operations but it does not avoid large positive ASI deviations after the return to power. The acceptability of these positive deviations depends on the available core margins for normal operation.

As transient case 10 shows, possibilities to improve mode K ASI control (magnitude and duration of ASI deviation reduction) exists by optimization of set-points like ASI target and corresponding bank initial positions, boron scenario, TAVG dead-band, bank worth.

The comparison between the maximum axial power peak value (FZ) reached after the return to high power level and the initial FZ value (i.e. the equilibrium value) allows to have a rough assessment of the loss of high linear power density (HLPD) margin during the transients. The magnitude of FZ variations are linked to ASI deviations. A better control of ASI after the return to power will reduce FZ magnitude variations.

At MOC the two transients, one with 40% reference overlap and the other with 60% reference overlap, present the same FZ increase value. At 90% EOC the similar transients show that using 60% reference overlap lead to a slight reduction of the FZ increase during the transient (19% instead of 16%).

The liquid waste amounts are linked to the used boron scenarios and xenon concentration variation during the transients. Values presented on Tables 2 and 3 are of the same order of magnitude as these obtained on French context. A more positive ASI target value or/and a narrow TAVG dead-band would decrease the amount of liquid wastes to be treated.

Tables 2 and 3 also show a large number of CEDM actuations during load follow transients, mainly during grid follow operation. It is noted that except in transient case 10 (ARS target = ESI +2.5%, TAVG width = 3℉) P2 performs always the higher number of steps, after P1 and R5 follow in a decreasing order.

It shows a large number of steps, mainly for banks P2, P1 and R5 during grid follow operation transients. The main reason is the very large (10% NP) remote control signal magnitude combined with the small worth of the bank inserted within the core at high power levels (around 170 pcm for P2). A further analysis will have to conclude if these figures are in accordance with CEDM functional requirements. In case of they are unacceptable, ways of reduction will have to be analyzed in a further phase of the project.

5. Conclusion and Further Study

The Mode K core control (average coolant temperature and axial shape index controls) has been reviewed based on a set of 10 typical transient simulations performed with FRAMATOME new simulator, SAF. The Mode K core control and all the main KNGR systems have been completely implemented in the simulator.

The transients that have been simulated allow to cover 3 burn-ups(BOC, MOC, 90% EOC), to cover all types of transient defined in KNGR performance requirements, to get sensitivity of performances to certain parameters such as bank worth, reference overlap, ASI dead-band, ASI target value, and to get sensitivity of performances to certain modifications of the boron scenario.

The analysis of Mode K performances show that the temperature is correctly controlled and there is no liquid wastes overproduction, and that the ASI is correctly controlled at part load, whatever the transient profile, the burn-up or the chosen set-points. Nevertheless, there are large positive ASI deviations for long time periods mainly after the middle of the cycle. The grid follow operation induces a high number of P2 and P1 bank steps, mainly due to the large remote control magnitude and to the small bank worth. The ASI control is not very sensitive to the reference overlap, but is degraded after the return to power when either the bank worth or the ASI dead-band are increased. The number of bank steps is not very sensitive either to the burn-up or to the ASI dead-band or to the reference overlap. It is decreased when the bank worth is increased but in that case the ASI control is degraded during grid follow operation after the return to power.

The best results as regards the ASI control are obtained under the following assumptions. First, ASI target increased of 2.5% (i.e., P2 slightly inserted before starting the transient) compared to the reference conditions with all banks out of the core. Second, temperature dead-band reduced from ±2°F to ±1.5°F.

References

[1] *KNGR SSAR*, Chapter 4, KEPCO (1999).

[2] *Korean Utility Requirement Document*, Rev. 0, KEPRI (1998).

[3] 오수열, *Mode K Description and Nuclear Design Data for KNGR*, NDL-07/98, KAERI (1998).

[4] M. Carrasco, *Results and Analyses of Mode K Load Follow Transients Simulated with SAF*, Framatome (1999).

[5] 김용희, *차세대원자로 기술개발 (II) - KNGR 부하추종운전 성능분석 및 Mode K 제어기법 최적화*, TR.95ZJ16.P1999.125, KEPRI (1999)

Burn-up (MWD/MTU)	Kind of Operation	Case No	ARS Set-point (%)	Reference Overlap (%)	Temp. Dead-band (°F)
500 (BOC)	Grid Follow Operation	1	1	60	2
		2	5	60	2
	Week-end Load Follow Operation	3	1	60	2
	Fast Reture-to-Power Operation	4	1	60	2
12000 (MOC)	Grid Follow Operation	5	1	60	2
		6	1	40	2
16000 (90% EOC)	Grid Follow Operation	7	1	40	2
		10	1	40	1.5
	Daily Load Follow Operation	8	1	40	2
	Fast Returen-to-Power Operation	9	1	40	2

Table 1. Simulation Cases

Burn up (MWD/MTU)			500 (BOC)				12000 (MOC)	
Transient identification	Case		1	2	3	4	5	6
	Frequency control signal		*	*			*	*
	Reference overlap (%)		60	60	60	60	60	40
	Fast return to power					*		*
	ARS set-point (%)		1	5	1	1	1	1
	Week-end operation				*			
Temp. deviation(°F)	Max. positive		4.3	4.0	3.5	3.3	4.0	4.0
	Max. negative		-3.6	-3.7	-3.3	-3.8	-3.6	-3.6
ASI deviation (%)	Max. positive	Value (%)	7.	10.	5.	3.	9.	9.
		Power level (%)	98.	97.	99.	91.	98.	97.
	Max. negative	Value (%): (1)	-3.	-6.	-5.	-2.	-5.	-2
		(2)	(-4.)	(-)	(-7.)	(-)	(-6.)	(-)
		Power level (%) (1)	89.	51.	54.	55.	55.	63.
		(2)	(98.)	(-)	(98.)	(98.)	(98.)	(-)
Total liquid wastes (E+3 lb)			18.	18.	37.	37.	29.	42.
Number of steps per bank (1 step = 0.75 inch)		P2	1708	1739	445	439	1678	1795
		P1	1036	1146	360	415	1023	1042
		R5	364	442	321	298	576	474
		R4	0	0	37	0	27	90
		R3	0	0	0	0	0	0
Axial power peak (Fz)	Max. value after the return to power: (1)		1.14	1.16	1.11	1.12	1.23	1.23
	(2)		(1.15)	(-)	(1.18)	(-)	(1.23)	(-)
	(initial value)		(1.10)	(1.10)	(1.10)	(1.10)	(1.09)	(1.09)
	Corresponding power level(%)		93.	97.	99.	100.	97.	97.

C : Current worth, I : Increased worth, DB : Dead-band value, N : No insertion limit reached

(1) : Maximum negative ASI deviation with a dilution at the end of transient.

(2) : Maximum negative ASI deviation without any dilution at the end of transient.

Table 2. Result Synthesis : BOC - MOC

Burn up (MWD/MTU)			16000 (90%EOC)			
Transient identification	Case		7	10	8	9
	Frequency control signal		*	*		
	Reference overlap (%)		40	40	40	40
	Fast return to power					*
	ARS set-point (%)		1	1	1	1
	Week-end operation		C	C	I	C
Temp deviation(°F)	Max. positive		3.6	4.4	2.7	3.4
	Max. negative		-4.2	-3.6	-2.6	-3.7
ASI deviation (%)	Max. positive	Value (%)	12.	10.	11.	11.
		Power level (%)	97.	98.	95.	98.
	Max. negative	Value (%): (1) (2)	 -4. (-12.)	 -3. (-)	 -4. -	 -4. (-10.)
		Power level (%) (1) (2)	 62. (98.)	 71. (-)	 53. -	 63. (101.)
Total liquid wastes (E+3 lb)			66.	88.	154.	216.
Number of steps per bank (1 step = 0.75 inch)		P2	1665	526	279	391
		P1	760	1596	156	348
		R5	429	796	30	328
		R4	94	174	0	90
		R3	0	0	0	0
Axial power Peak (Fz)	Max. value after the return to power: (1) (2) (initial value)		 1.29 (1.32) (1.15)	 1.31 (-) (1.15)	 1.27 - (1.15)	 1.26 (1.28) (1.15)
	Corresponding power level(%)		96.	98.	98.	98.

C : Current worth, I : Increased worth, DB : Dead-band value, N : No insertion limit reached

(1) : Maximum negative ASI deviation with a dilution at the end of transient.

(2) : Maximum negative ASI deviation without any dilution at the end of transient.

Table 3. Result Synthesis : 90% EOC

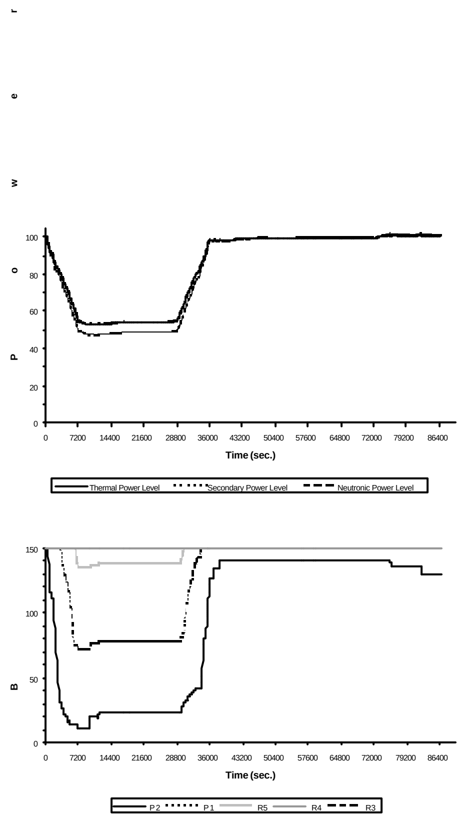

Figure 1. Power Level-Bank Positions

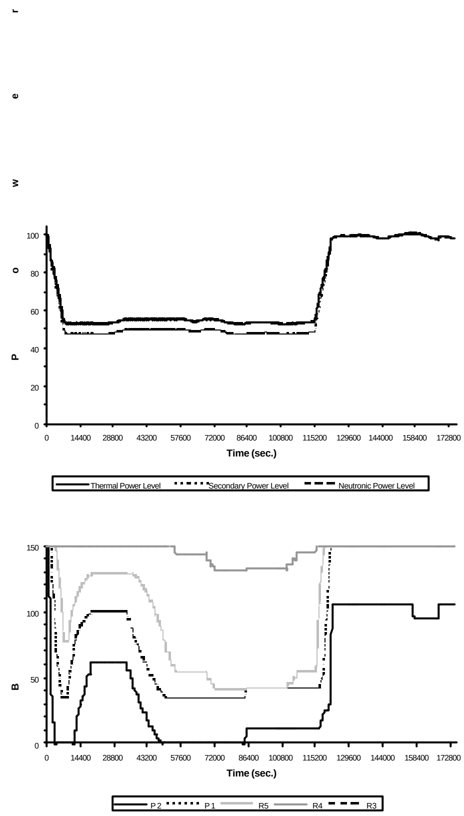

Figure 2. Power Level-Bank Positions

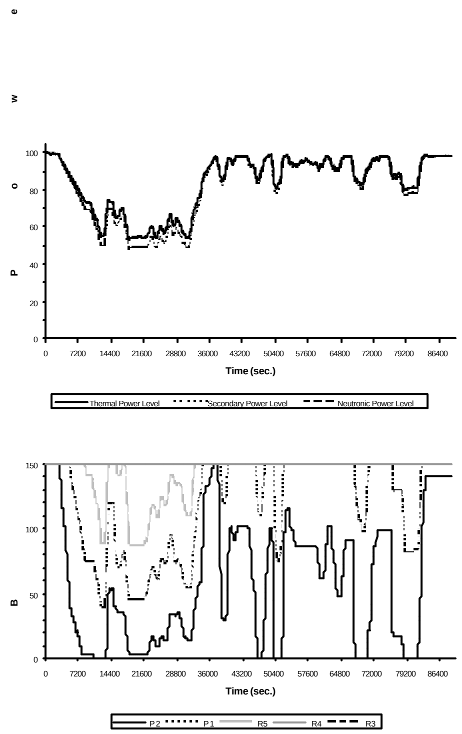

Figure 3. Power Level-Bank Positions

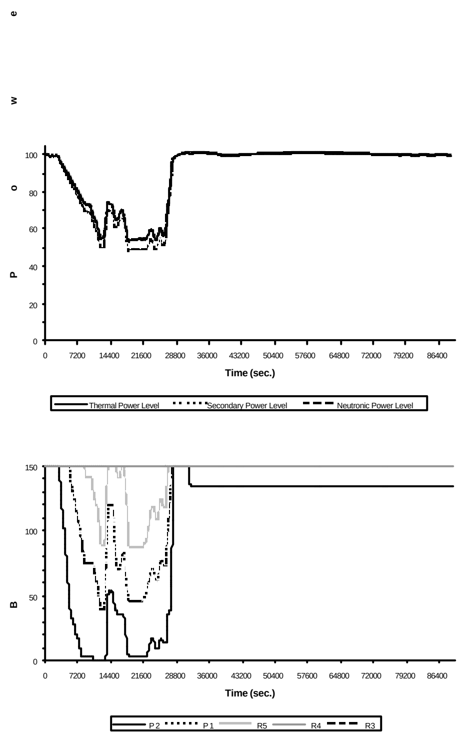

Figure 4. Power Level-Bank Positions

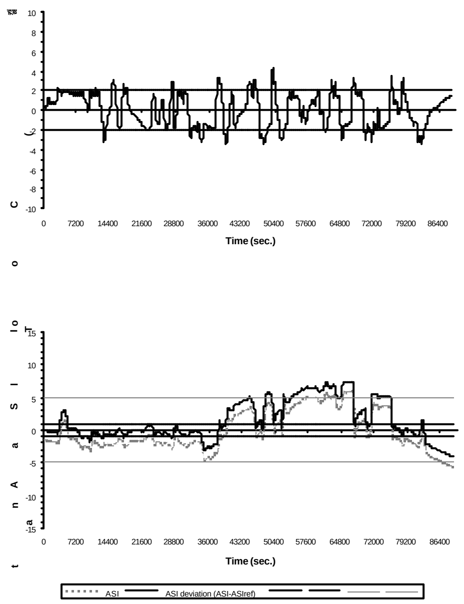

Figure 5. Case 1 -T° Deviation-ASI

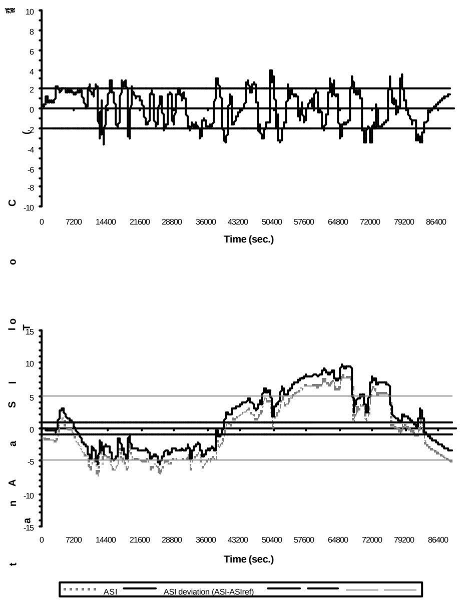

Figure 6. Case 2 - T° Deviation-ASI

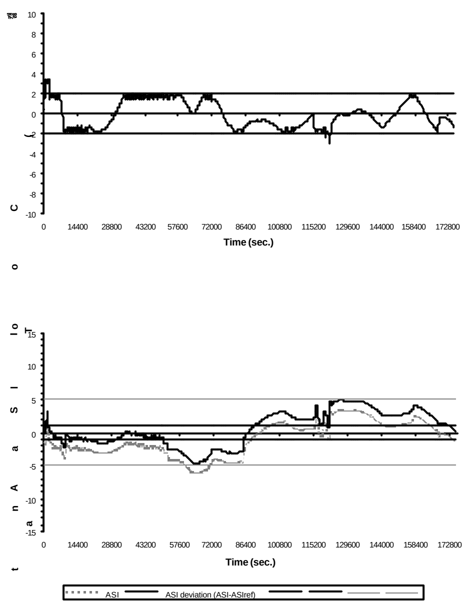

Figure 7. Case 3 -T° Deviation-ASI

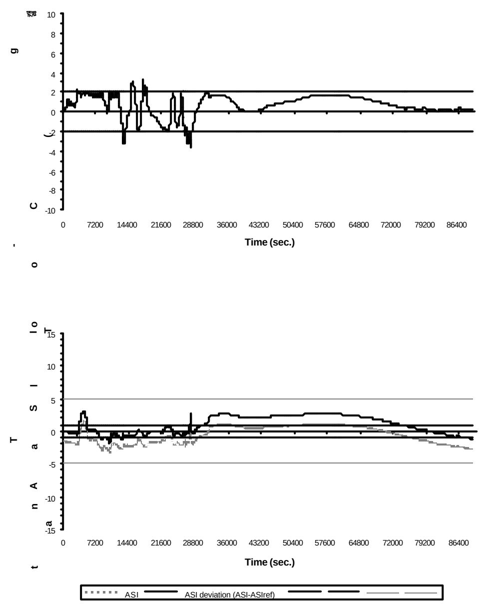

Figure 8. Case 4 - T° Deviation-ASI

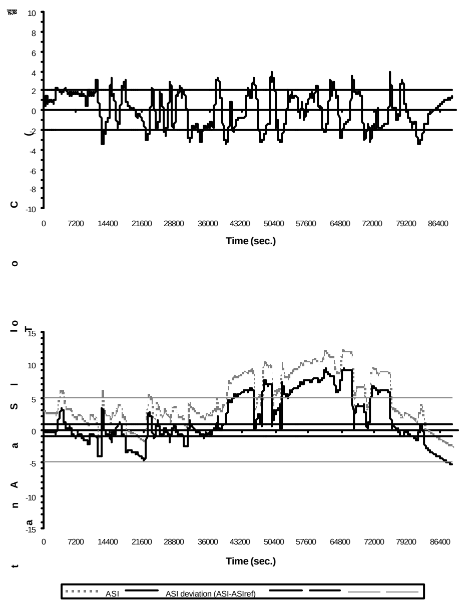

Figure 9. Case 5 -T° Deviation-ASI

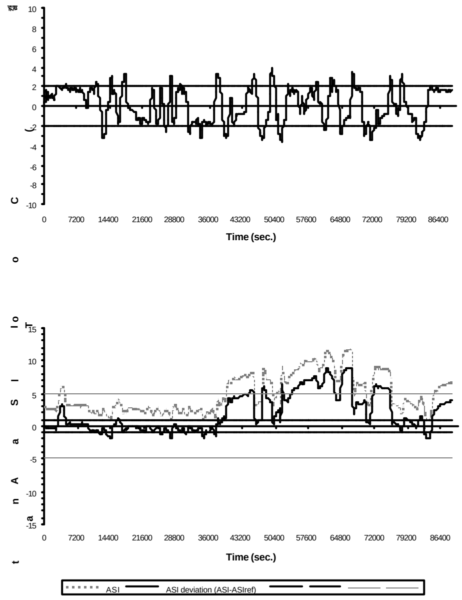

Figure 10. Case 6 - T° Deviation-ASI

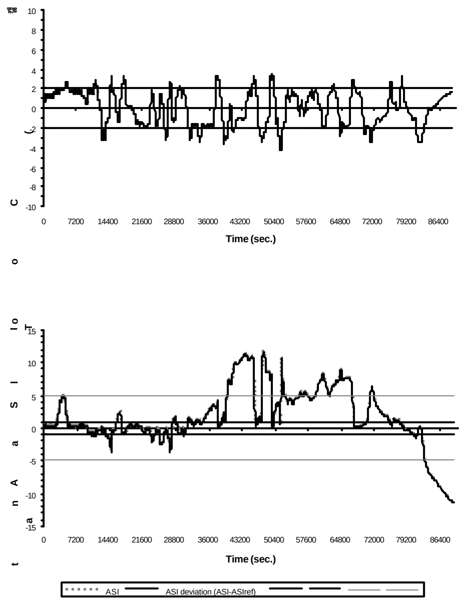

Figure 11. Case 7 -T° Deviation-ASI

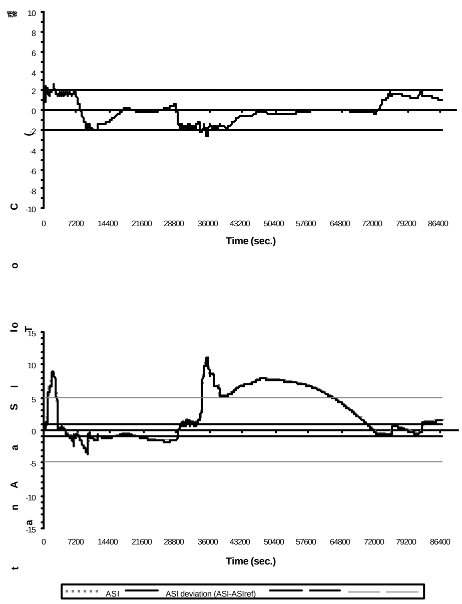

Figure 12. Case 8 - T° Deviation-ASI

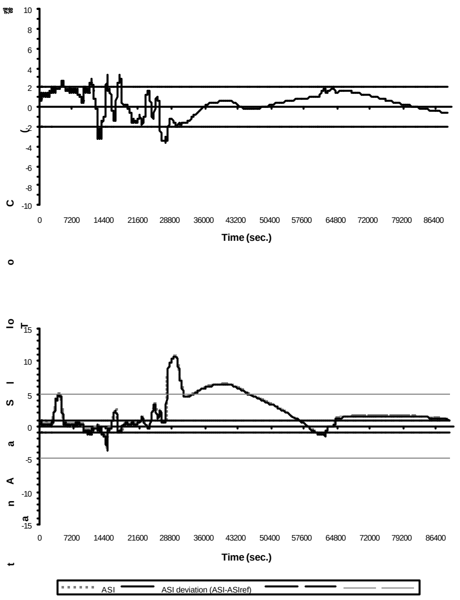

Figure 13. Case 9 -T° Deviation-ASI

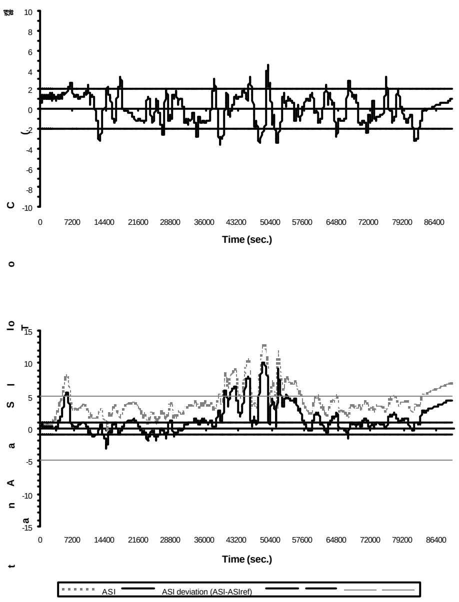

Figure 14. Case 10 - T° Deviation-ASI