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Conceptual Development of the Plant Operations Regulator for Nuclear Power Plant Operating Flexibility

Jung-In Choi, Myeong-Hoon Lee, In-Ho Song, Soo-Youl Oh, and Yung-Joon Hah

Korea Atomic Energy Research Institute, Taejon, Korea
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원전 운전 유연성 향상을 위한 운전 조정기 개념의 개발

최중인 · 이명훈 · 송인호 · 오수열 · 하영준

한국원자력연구소
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Abstract

The conceptual design of the Plant Operations Regulator (POR) is presented for the pressurized water reactor plants. The POR is a digital supervisory limitation control system. The POR assures that the plant does not exceed the operating limits by regulating the plant operations through monitoring the operating margins of the critical parameters. The POR is aimed at increasing the operating flexibility which allows the nuclear plant to meet the grid demand in very efficient manner. It responds to the grid demand without penalizing plant availability by limiting the load demand or by modifying the plant control schemes when the operating limits are approached or violated. The POR design concepts were tested using simulation responses of the 1000 MWe pressurized water reactors, Yonggwang Units 3 & 4. The simulation results illustrate that the POR can be used to improve operating flexibility.

요 약

가압경수로형 원전을 위한 운전조정기의 개념 설계를 수행하였다. 운전조정기는 디지탈 감시 제한 계통으로서, 원전의 주요 운전 인자들을 감지하여 운전 제한치를 벗어나지 않도록 조정한다. 이는 운전 유연성을 향상시켜서 원전이 전력망 요구에 효과적으로 대처할 수 있도록 한다. 운전 허용 범위를 넘어서는 전력망 요구에 대해서 이를 제한하거나 제어 체계를 변경함으로써 이용률에 영향을 주지 않으며 운전을 수행할 수 있도록 한다. 이 개념은 1000 MWe급 가압경수로인 영광 3, 4호기의 거동 모의를 통하여 평가되었다. 그 모의 계산 결과 운전 조정기가 원전의 운전 유연성 향상을 위하여 유용하게 사용될 수 있음을 보여 주었다.

1. Introduction

The nuclear units have been limited in operating flexibility due to their specific concerns on safety. In comparison to conventional plants, nuclear plants permit rather narrow operating ranges, beyond which they conservatively react to disturbances by a protective action. Frequent actuations of the protection system may result in the penalties in plant safety as well as in plant availability. For these reasons, most nuclear plants have not been exposed to the disturbances due to load changes such as load–follow operation including frequency control. In this paper, the Plant Operations Regulator (POR) is presented as a limit a tion system for the pressurized water reactors (PWRs). The limitation system is introduced in the nuclear plant based on the defence–in–depth operation concepts. The first line of defence is the operational control system that maintains the process parameters within the normal conditions in an automatic manner. The last line of defence is the protection system that reserves the plant safety when the parameters challenge the safety limit. The concept of limitation system is the "gray" function between the control system ("white") and the protection system ("black"), which countermeasures the disturbances beyond the control capability by regulating the plant operations before the event grows from minor disturbances to a significant incident needed for the actuation of the protection system. One of the limitation system is the human operator. The POR is the automatic supervisory limitation system replacing the human actions with a digital computer. This system may get credit for :

–early and intelligent initiation of proper limitation actions, contributing to more careful treatment of the plant by smoothening transients and acting as a fast back–up control ;
–reduction in probability of human error by minimizing the operator's burden ; and
–increase in plant operating flexibility and availability by allowing better and more sophisticated control means for permitting operation much closer to limits as possible without penalizing the plant safety.

The POR has evolved from the Megawatt Demand Setter (MDS) which was developed through the Korea Atomic Energy Research Institute/Asea Brown Boveri–Combustion Engineering (ABB–CE) Joint R&D program and implemented into the SYSTEM 80^+ design [1,2]. The MDS was designed to perform its limitation functions with the basis on the manual operation for reactor power control, thus always being accompanied by the human operator. It proved to be less useful in practical application. The POR, in conjunction with the automatic reactor power control system, has been largely extended in the degree of automation as a supervisory limitation system, evolving from the complement to the substitute for the human actions.

2. The Design Bases

·The POR is constructed to perform on–line monitoring of the operating margin for critical plant parameters and to limit the turbine load or to modify the control schemes to maintain the adequate operating margin. During load maneuvers, the POR screens load change requests through the turbine control system (TCS) to avoid driving plant parameters beyond their operating limits. It regulates the plant operations in a feedback manner. In addition, the POR will initiate its limitation action by modifying the plant control schemes through the associated control systems if they do not function properly. It regulates the plant operations in a feedforward manner. Figure 1 illustrates the functional block diagram of the POR.

There are various limits which may require the plant operations to be regulated by the POR. These design bases limits for the POR include the Nuclear Steam Supply System (NSSS) process parameters limits, the feedwater limits, the core limits, the turbine limits, and the manual limits. These can be described as follows :

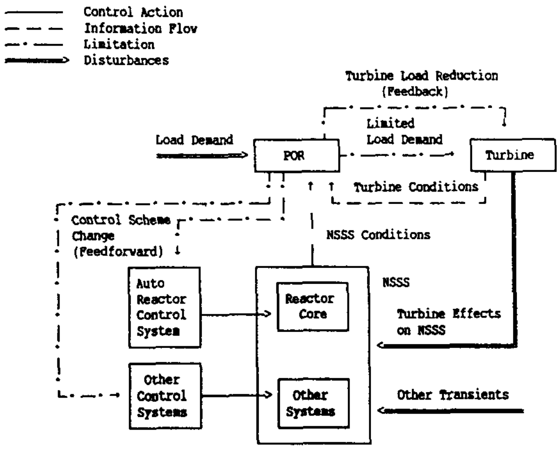

Fig. 1. Design Concept of Plant Operations Regulator

NSSS Process Parameters Limits

A rapid increase in the turbine load may cause a drop in the primary coolant temperature if there is a delay in the appropriate increase in reactor power. Such a decrease in the coolant temperature can be substantial enough to challenge the low trip limits of the primary and the secondary pressures. The POR is designed to monitor the primary and the secondary pressures and to regulate the plant operations based on the proximity to the trip limits of these variables, if necessary.

Feedwater Limits

In some cases, the plant load may exceed the feedwater pumping capacity. In such cases, the POR prevents a trip due to the resulting low steam generator water level by reducing the loading rate as needed. For this purpose, the POR is designed to monitor the proximity of the steam generator levels to their low trip limits.

Core Limits

A load transient can lead to a xenon–induced transient or other core related phenomena which may cause the core to approach its licensed power operating limit or trip limit for the Departure from Nucleate Boiling Ratio (DNBR) or the Linear Heat Rate (LHR). The POR is designed to monitor the margin to operating limits through the Core Operating Limit Supervisory System (COLSS) and the margin to trip limits through the Core Protection Calculator (CPC) and to initiate proper limitation actions based on the proximity to the limits.

Turbine Limits

The POR stops loading for the following turbine conditions :

–Turbine power/load unbalance,
–Turbine initial pressure limit,
–Turbine control valve wide open, and
–Turbine load limit.

The POR receives status and limit signals from the TCS for the conditions listed above.

Manual Limits

The operator can regulate the plant operations by setting the manual limits under the limiting plant conditions that are not monitored by the POR. Manual limits set by the operator can override all other limits.

3. Limitation Algorithm

The POR algorithms consist of the feedback limitation and feedforward limitation as follows :

3.1. Feedback Limitation Algorithm

The POR takes a limitation action in a feedback manner by changing the turbine load, which indirectly regulates the plant operating variables. Figure 2 shows a simplified version of the POR feedback algorithm. The POR compares the electrical generation and the load setpoint from the automatic dispatching system (ADS) or from the POR operator's module (POROM). And it generates a loading rate proportional to this difference but limited by the operator set rate. This rate is compared to the POR override rate. The override rate is generated in the POR Limit Program as shown in Fig. 3. The margin to limit of each critical variable is processed into a load ramp rate throιgh a compensator with a proportional and a derivative term (P+D). The proportional term reduces the limit rate as the critical variable nears its limit. The derivative term senses the rate at which the margin to limit is decreasing. This term acts to reduce the limit rate more for the critical variable

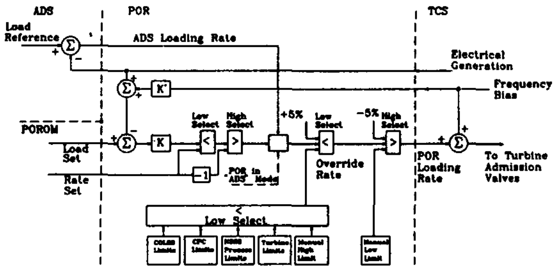

Fig. 2. POR Feedback Limitation System

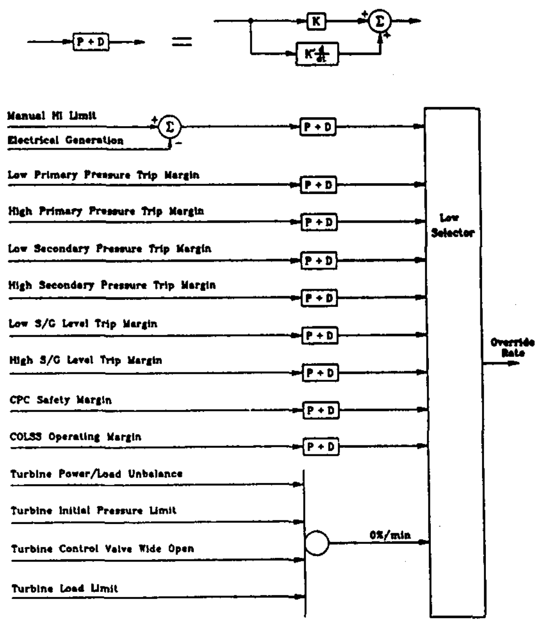

Fig. 3. POR Override Rate Calculation Algorithm

that is more rapidly approaching its limit. It is noted that the manual high limit set via the POROM is also employed as an operating limit in the override rate calculation. In addition, the POR Limit Program generates an override rate of zero upon receiving any one of several turbine limits. The most restrictive of the calculated limit rate is called the override rate. The override rate is compared to the load demand rate, limited to 5% per minute. The low selector passes the lower of these rates to the TCS. The resulting signal drives the TCS load reference motor, which controls the TCS load reference setpoint. If a negative rate is generated for a critical variable, the plant load is reduced even without a load change demand.

3.2. Feedforward Limitation Algorithm

The POR is also designed to take a limitation action in a feedforward manner by modifying the plant control schemes, which directly regulates the plant operating variables. The feedforward limitation acts faster and more effectively on the challenging plant operating variables than the feedback limitation does. Figure 4 provides a conceptual demonstration for the feedforward algorithm. Similar to the feedback algorithm, the margin to limit of each critical variable is processed into a load ramp rate through a compensator with a proportional and a derivative term (P+D). The feedforward algorithm includes a Decision Making Module (DMM), which identifies the plant malfunction status resulting in the most limiting variable and then makes a decision to take a proper limitation action. For the reactor power control system, the DMM algorithm including limitation actions has been developed, which will be detailed in the section 5.2. The DMM features for the other NSSS control systems are remained for further development.

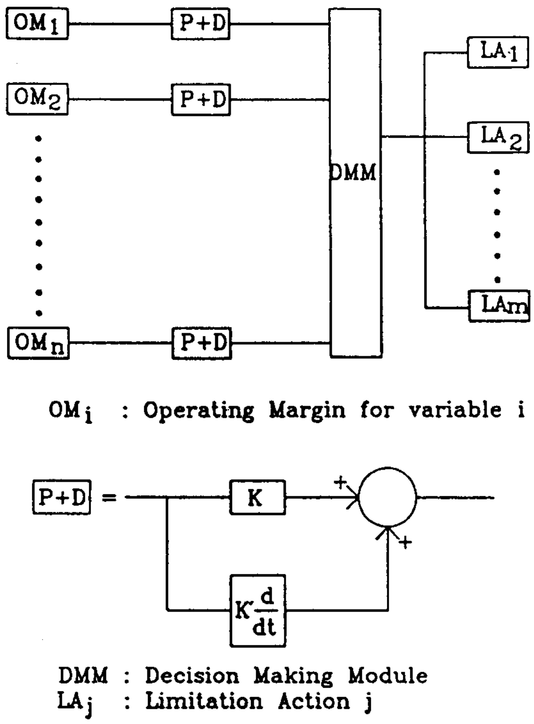

Fig. 4. POR Feedforward Algorithm

4. Hardware Features

The POR, newly developed in this study, has not been implemented in hardware. The hardware features for the POR system are to be provided as follows :

The POR will be designed as a stand–alone system that consists of a controller, an operator's module, power supplies and hardware for interfacing with other systems. The POR controller is a microprocessor located in the control element drive mechanism control system (CEDMCS) cabinet. It consists of the software programs and the associated hardware components. The POR controller software consists of the following software modules :

Executive Modules

–Operating systems ;
–Interface handler ;
–Internal clock handler ; and
–Utilities software (assembler, loader, etc.).

Application Programs

–Mode select ;
–Limitation algorithms ;
–Input processing ;
–Output processing ; and
–POROM display software.

Diagnostic Software

–On–line diagnostics ; and
–Off–line diagnostics

The POR limitation algorithm was detailed in the previous section.

The POR performs its mission functionally interfacing with the ADS, the TCS, the plant protection system (PPS), the CPC, the plant monitoring system (PMS), and other NSSS control systems.

The POR/ADS interface provides following signals : ADS load demands (ADS to POR) ; and POR status information (POR to ADS). The POR/TCS interface provides following signals : POR loading rate (POR to TCS) ; TCS mode change commands (POR to TCS) ; Electrical generation (TCS to POR) ; and Turbine limits (TCS to POR).

Through the POR/PPS interface, the PPS transmits concerned plant process variables and their trip setpoints to the POR. Also, through the POR/CPC interface, the POR is provided with core overpower margins from the CPC. The POR interfaces to the PPS and the CPC are equipped with the isolator to ensure electrical independence. Regarding the use of protection signals (PPS and CPC), the POR performs signal validation in order to prevent a violation of Control/Protection system interaction design requirements. The signal validation logic is demonstrated in Fig. 5.

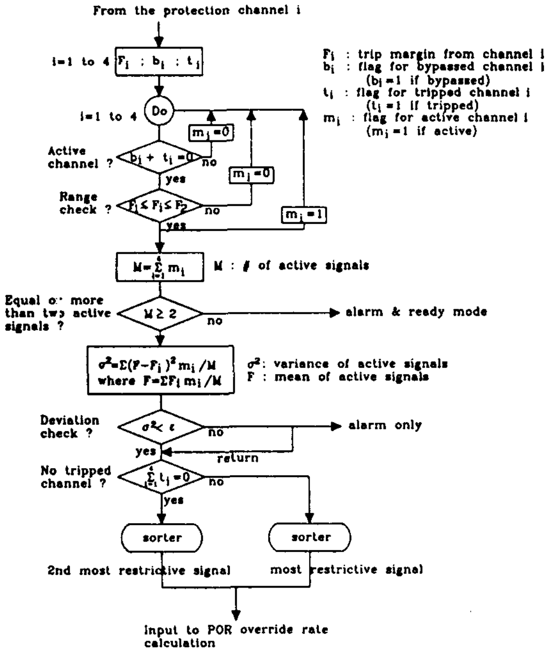

Fig. 5. Signal Validation Logic of POR for Protection Channels

When a channel is bypassed or tripped, the signal from that channel is not considered as an active signal. The out-of-range signal is not considered, either. If there are less than two active signals available, the POR will generate an alarm and go to the standby mode. Only active signals are put into the sorter which selects the second to most restrictive value. This value is selected to correspond to the PPS and CPC trip logic which functions in two out of four conincidence. If there exists a tripped channel, the sorter selects the most restrictive signal in order to correspond to the two out of four trip logic. The selected value is then used in the rate calculation of the POR Limit Program as described in section 3.1. It is noted that a random deviation check is performed for active signals. If they fail, an alarm is generated in order to inform the operator that active signals are largely deviated from one another.

The POR/PMS interface consists of digital data links. This interface provides the following information : COLSS core overpower margins (PMS to the POR) ; and POR status information for displays (POR to PMS).

Finally, the POR interfaces with the NSSS control systems for the feedforward limitation algorithm. The POR recieves the status information from each NSSS control system and sends the control signals based on the modified control schemes decided by the POR DMM as described in section 3.2.

5. Testing and Functional Evaluation

The simulation results of the Yonggwang Units 3 & 4 (YGN 3 & 4) plant responses during load maneuvers are used for testing and functional evaluation of the POR design concepts. The YGN 3 & 4 are the 1000 MWe ABB/CE type PWR plants. The evaluation scheme of the POR is depicted in Fig. 6. For the feedback algorithm, the limited situation due to NSSS process parameters was simulated. And for the feedforward algorithm, the core limited situation was simulated.

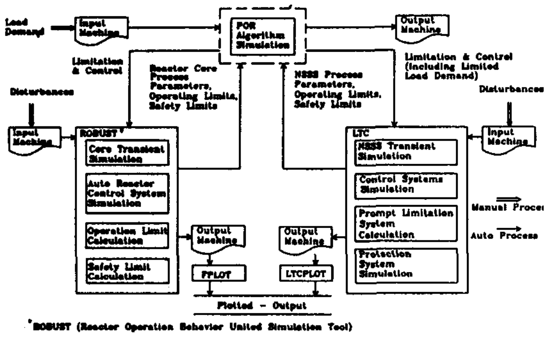

Fig. 6. POR Design and Evaluation Scheme

5.1. NSSS Process Parameter Limits

It is found that the POR can prevent a trip due to perturbed NSSS process parameters during a fast load maneuver by limiting the loading rate to keep the parameters within their proper operating limits. When a rapid load increase is required, the turbine admission valve is opened to increase the heat removal rate from the primary coolant, consequently, lowering the core inlet temperature. Due to the negative temperature coefficient, the core reactivity increases, producing more power to match the steam demand. Until core power is increased to the demand by other means, the average coolant temperature (T_{avg}) will remain below the programmed value for the higher power level. In order to restore T_{avg} to its programmed value, the core reactivity needs to be increased by either withdrawal of the control rods or dilution of the boron concentration. If the reactivity compensation is delayed due to slow rod control or boron dilution, the decrease in the coolant temperature may be sufficient to cause the primary and the secondary pressures to challenge their trip limits.

The POR is designed to monitor the proximity of these parameters to their trip limits and to reduce the loading rate as needed to avoid a trip on those parameters. The ability of the POR to perform this capability was demonstrated by simulating the YGN 3 & 4 NSSS responses to a rapid load increase. For this purpose, an ABB/CE code, LTC[3], was used. The LTC code is a best estimate NSSS transient analysis code, used in the commercial ABB/CE type NSSS design. It is judged that the LTC is an adequate tool to simulate the NSSS related design bases events for the POR. As shown in Fig. 6, the code includes models of all NSSS control systems.

To simulate automatic reactivity control via the control element assemblies (CEAs), LTC includes a routine to simulate the reactor regulating system (RRS). The delay in reactivity compensation due to slow control rod movements was simulated by reducing the CEA speed in the RRS routine of LTC. Figure 7 illustrates the simulation of such a load increase without the POR. The simulation begins with 5% per minute ramp–up from 50% of rated power. Prior to the ramp–up, the plant has been operating in a nearly steady manner at 50% of rated power. As the turbine load increases with a delay in reactivity compensation by the control rod, the reactor coolant temperature decreases until the reactor power matches the turbine load by the negative moderator temperature coefficient. As shown in the second part of Fig. 7, T_{avg} decreases far below its programmed value, causing the primary and the secondary pressures to decrease sufficiently to challenge their low trip limits. The lower illustration in Fig. 7 presents the secondary pressure, which was found to be the more critical parameter. The secondary pressure violates its low trip setpoint of 913 psia at 390 sec, causing a reactor trip. Indicated in Fig. 8 is the imple-

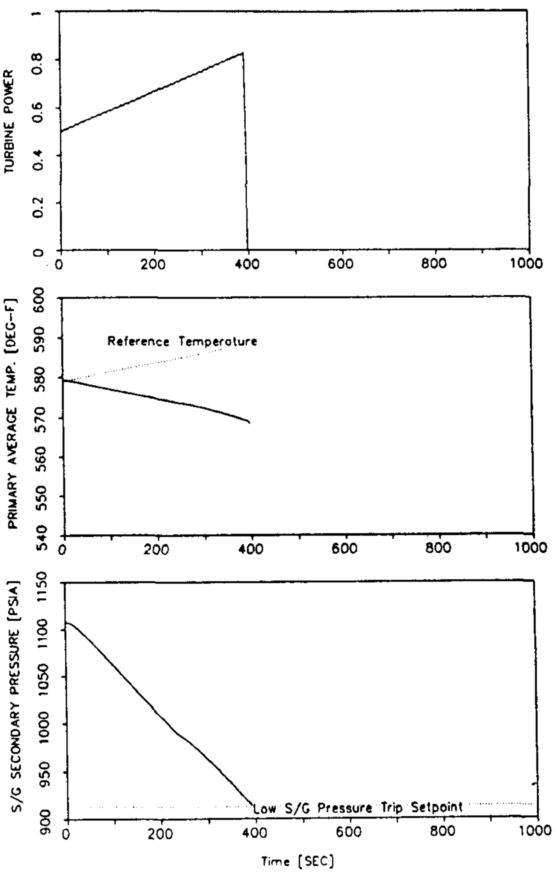

Fig. 7. NSSS Process Parameter Responses to a Fast Load Increase Without POR

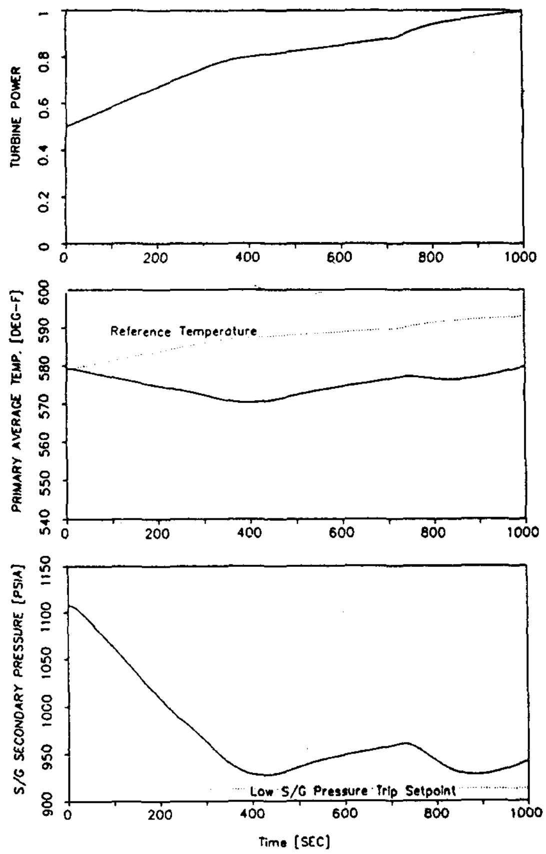

Fig. 8. NSSS Process Parameter Responses to a Fast Load Increase with POR

mentation of the POR concepts for the same load maneuver which avoid tripping the plant due to perturbed NSSS parameters. The POR monitors the proximity of the primary and the secondary pressures to their trip limits and reduces the loading rate as needed to avoid the trip. In Fig. 8, the POR starts actuating its limiting action on load rate at 350 sec, thus allowing T_{avg} to be restored to its programmed value, even with slow reactivity compensation. Then, the secondary pressure is restored to a value which allows sufficient margin to its operating limit to prevent a trip during remainder of the load increase. It appears that during a fast power increase the POR can automatically intercede to reduce the loading rate to avoid exceeding NSSS parameters operating limits.

5.2 Core Limits

The second case demonstrates that the POR can avoid a violation of core operating limits during a load transient. Major load transients can result in large perturbations to the power distribution in the core. If these are not properly controlled, regions of high power density can occur, possibly challenging the core operating or trip limits when combined with xenon effects. These core limits are based on the values which provide adequate margin to the DNBR and LHR limits determined in the plant safety analysis.

A new power control strategy was developed in parallel with this investigation [4] for the automatic reactor power control system. In this strategy, the bank with the high reactivity worth (HROD) is dedicated to the axial power shape control and other regulating banks (RRODs) are used for the reactivity compensation. They are designed to provide monotonic relationship between the motion of HROD and the change of the axial power shape irrespective of the motion of the RRODs for compensating the core reactivity due to the motion of the HROD. When this relationship exists, automatic axial shape control can be achieved with a simple control logic. Thus, the reactor power can be automatically regulated both for the reactivity and for the power shape by using double closed-loop control of T_{avg} and ΔI. The ΔI is the axial power difference defined as follows:

$$\Delta I = P_t - P_b$$

where P_t : top half power

P_b : bottom half power

It is demonstrated schematically in Fig. 9.

The core limited situation may occur under the limiting cases where the automatic power shape control scheme does not function properly. These limiting cases are listed in Table 1. As the core operating limit is approached, the POR initiates a limitation action which modifies the existing auto-

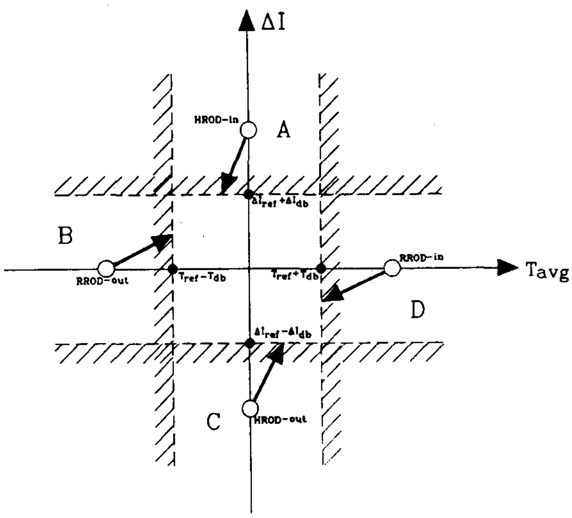

Fig. 9. Automatic Reactor Power Control Operating Diagram

matic control scheme. The limitation actions of the POR corresponding to the combinations of operating region, shown in Fig. 2, and the limiting case, listed in Table 1, are tabulated in Table 2. The POR is designed to monitor the margin to these core limits and to initiate a corresponding limitation action to the limiting cases under which the automatic reactor power control scheme does

Table 1. Limiting Cases of Automatic Reactor Power Control

CASE	RROD	HROD
1	PDIL	O.K
2	O.K	IL
3	PDWL	O.K
4	O.K	OUT
5	PDIL	IL
6	PDIL	OUT
7	PDWL	IL
8	PDWL	OUT

PDIL : Power Dependent Insertion Limit
PDWL : Power Dependent Withdrawal Limit
IL : Insertion Limit(Constant)
OUT : fully withdrawn
O.K : RROD or HROD does its function

Table 2. POR Limitation Actions

Operating Region	Limiting Case	POR Limitation Actions
A	1	Normal
	2	RROD–IN, Boron Dilution
	3	Normal
	4	Normal
	5	Not Happened
	6	Normal
	7	RROD–IN, Boron Dilution
	8	Normal
B	1	Normal
	2	Normal
	3	Boron Dilution, or Relax PDWL(EOL)
	4	Normal
	5	Normal
	6	Normal
	7	Boron Dilution, or Relax PDWL(EOL)
	8	Boron Dilution, or Relax PDWL(EOL)
C	1	Normal
	2	Normal
	3	Normal
	4	RROD–OUT, Boration
	5	Normal
	6	RROD–OUT, Boration
	7	Normal
	8	Relax PDWL, or Power Reduction
D	1	Boration
	2	Normal
	3	Normal
	4	Normal
	5	Boration
	6	Boration
	7	Normal
	8	Normal

not function as designed to provide adequate margin.

The ability of the POR to perform this function was evaluated by simulating the YGN 3 & 4 core responses to a major load transient. The YGN 3 & 4 core was simulated by using a core transient code, ROBUST[5]. The on-line calculation of the core limits performed by the COLSS and the CPC can also be simulated by using ROBUST. The code of ROBUST has been developed based on the ABB/CE codes, FLAIR[6], COLSIM[7] and CPCSIM[8], which are used in the commercial ABB/CE type core design. The ROBUST is only valid for the slow core transient analysis. The core related design bases events for the POR system are judged to be slow enough to use ROBUST code. Figure 10 illustrates the power maneuver performed with automatic reactor power control. The maneuver begins at 100% power, ramp down to 50% power over 2 hours, and then holds at 50% for 6 hours, ramps back to 100% power over 2 hours, and then holds at 100% for 14 hours. Some of the important core parameters could be plotted during the maneuver. Along with the core power, the power operating limits (POL) determined by the COLSS and the safety limits by the CPC are plotted in the bottom of the Fig. 10. The COLSS determines the operating limit on core power and generates an alarm when necessary. The CPC determines the limit on core power at which the reactor will be tripped. Generally, there is more margin to the CPC trip limit than COLSS operating limit.

In Fig. 10, the core is initially at equilibrium xenon at 100% power with all rods fully withdrawn except the HROD. The maneuver is performed at 2,000 MWD/MTU burn-up state by using the RRODs for reactivity control with adjustment in boron concentration and the HROD for axial power shape control. At 8 hrs, the RRODs are pulled sequentially by group to ramp from 50% to 100% power in two hours. After resuming 100% power, xenon effects are compensated by inserting the RRODs as necessary to maintain total core reactivity but without regarding for the power shape. Then, the axial power shape shifts downward even with the HROD fully withdrawn. In this case, the automatic shape control scheme lies under one of the limiting cases listed in Table 1. Figure 10 shows that local peaking in the power distribution results in a sharp decrease in the operating limits after returning to the rated power level. When one or more of the operating limits

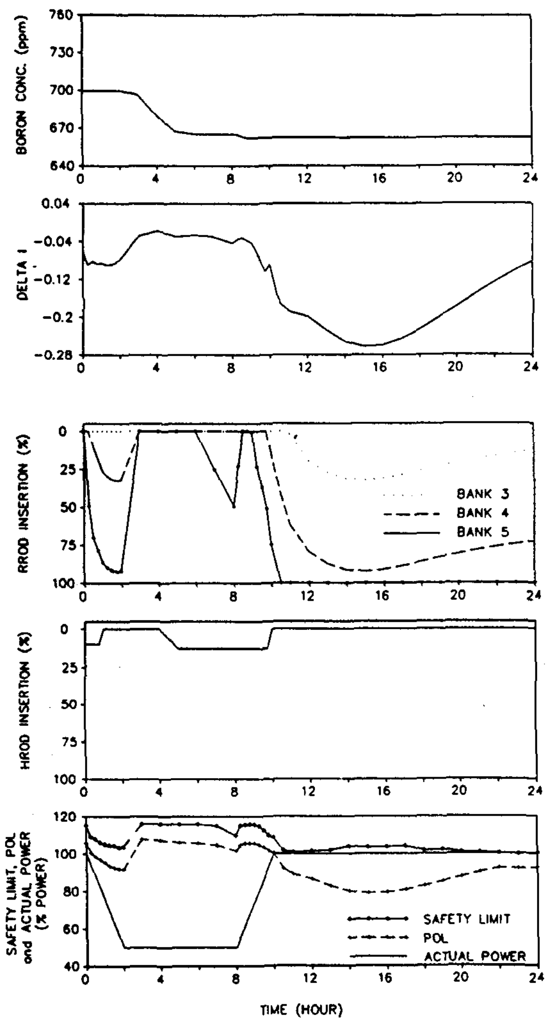

Fig. 10. Reactor Core Parameter Responses to a Daily Load Maneuver without POR

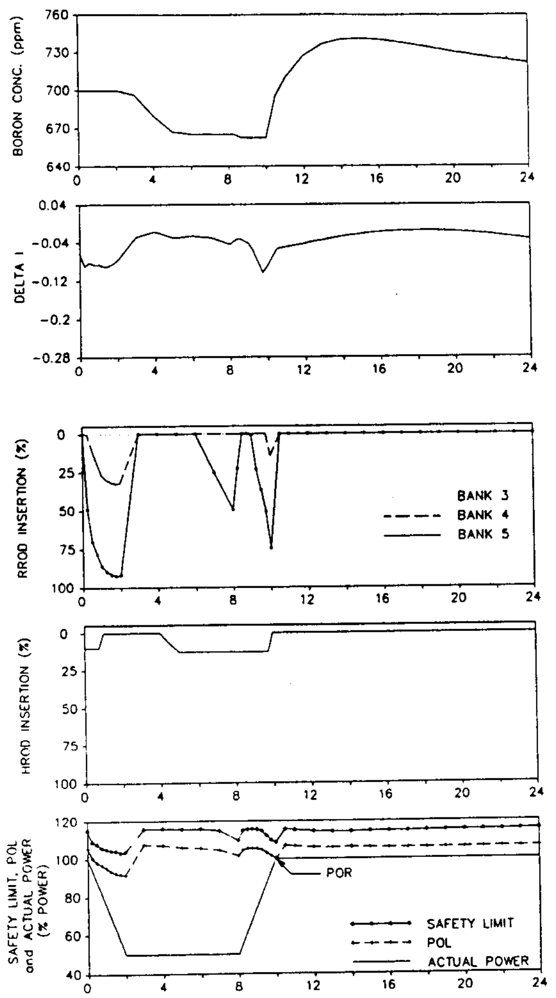

Fig. 11. Reactor Core Parameter Responses to a Daily Load Maneuver with POR

are exceeded at 10 hrs, the COLSS generates an alarm. Unless appropriate actions are taken, a trip by the CPC will occur. Without the POR, a reduction in power by the operator would be necessary to prevent a reactor trip.

The POR is designed to perform automatically one of the limitation actions listed in Table 2 in response to reduction in the operating limits calculated by the COLSS. The simulation to demonstrate the concepts of using the POR in a scenario of this type is given in Fig. 11. The power maneuver in Fig. 11 is the same as in Fig. 10 until returning to the 100% of the rated power level at 10 hrs. Following that point, the effect of using the POR is illustrated. As can be noted, there is less margin to the COLSS operating limit, subsequently, the COLSS limit is the first to respond to the increase in power peaking. In this case, the POR initiates a limitation action to maintain acceptable operating margin with the COLSS limit. The limitation action modifies the control scheme such that the boron is used for xenon reactivity compensation instead of the RRODs. Thus, by initiating the limitation action to comply with the COLSS limit, the POR prevents a violation of the COLSS operating limits which may initiate a reactor trip. After returning to the rated power level with the aid of the POR, adequate margins to the COLSS and the CPC limits are maintained. The results indicate that the POR allows the plant to perform the continuous full power operation without violating the operating limits or the safety limits.

6. Conclusions

The design concepts of the POR have been developed for the pressurized water reactor plants to provide higher operating flexibilty without penalizing plant availability and safety. These concepts were evaluated based on the simulation of the YGN 3 & 4 plant responses. The simulation results demonstrated that the POR would improve operating flexibility. With further refinements for detailed design phase, the POR is recommended to be incorporated into the Korean Standardized Nuclear Power Plants as one of the Korean specific design features.

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