Proceedings of the Korean Nuclear Society Spring Meeting
Pohang , Korea, May 1999

An Adaptive Controller for Wolsong NGS Bulk Liquid Zone Control of RRS

Oon-Pyo Zhu, Bok Ryul Kim, Seong Hyon Ji
Korean Institute of Nuclear Safety

Kern Joong Kim
Choong Nam National Univ.

Abstract

The evaluation and inspection of linear stability of Liquid Zone Controller (LZC) has been being performed with design data and actual program parameters installed in plant Digital Control Computers (DCC) during licensing stage of Wolsong Units 2,3 and 4. The study was done to identify the candidates – the vulnerable devices or control parameters on stability when plant is undergone with improper tuning or control components' aging. The time constant of LZC valve was analyzed as the critical parameter among the candidates. However, the surveillance requirements could not be applied to the process control system such as control devices of RRS. The response time of RRS controllers have not been measured since commissioned. The fine tuning parameters and gains should have been justified with an analysis, but is tuned with experiences learned from previous CANDU plants. With limited simulation results, we have confirmed that no fundamental barriers of RRS bulk control for Wolsong 2/3/4 exist. The dynamic calibration in DCC program could correct continuously a wrong input-sensing signal of log neutron power such like an adaptive system. The first order lag term of the actuator, LZC valve, is the most critical among other sensing and actuating devices. It is, however, a quite large degradation from design value when it disturbs the plant. With a help of MRAS (model reference adaptive system) regulator in this study, the adaptive controller with an aged actuator has a possibility to cope with the worst situation with which the DCC program could not deal. It will give guidance for plant engineer when the tuning is necessary or preventive maintenance is planned against aging. If a fault tolerant control scheme is applied, an unstable operation of RRS will be relieved from such an unexpected malfunction. We recommend that the precautions and limitations for dynamic response of LZC be considered to apply the vulnerable parameters identified in this study. In this study we suggest an adaptive controller to follow the Reference Model to cope with an aged and degraded effect on the LZC controller.

1. Introduction

The Reactor Regulating System (RRS) of CANDU type Wolsong NGS for Liquid Zone Controller (LZC) uses a linear control. There is a Significant Event Report, which describes that the control valves of the RRS in Bruce Unit 7 started to oscillate or to pulsate with 6

Hz. The cause is the natural frequency of the resonance between mechanical piping and the controllers. The evaluation and inspection of linear stability of LZC has been being performed with design data and actual program parameters installed in plant Digital Control Computers (DCC) during licensing stage of Wolsong Units. The study was done to identify the candidate – the vulnerable sensing and actuating devices or control parameters on stability when plant is undergone with improper tuning or control components' aging.

The time constant of LZC valve was analyzed as the critical parameter among the candidates. All the critical parameters of Special Safety Systems should be confirmed by dynamic response measurements thoroughly for the first time in CANDU family♣. However, the surveillance requirements could not be applied to the process control system such as actuators of RRS. We recommend that the precautions and limitations for dynamic response of LZC be considered to apply the vulnerable parameters identified in this study. In this study we suggest an adaptive controller to follow the Reference Model to cope with an aged and degraded effect on the LZC controller

2. System Modeling [1]

2.1 Reactor Modeling

A nuclear reactor point kinetics model is applied to six group equations. Differential equations are linearized with perturbation theory as follows.

$$d\frac{n(t)}{dt} = \frac{\boldsymbol{r}(t) - \sum_{i=1}^{6} \boldsymbol{b}_i}{A} n(t) - \sum_{i=1}^{6} \boldsymbol{l}_i C_i \qquad \text{..................................(1)}$$

$$d\frac{C_i(t)}{dt} = \frac{\boldsymbol{b}_i}{A} n(t) - \boldsymbol{l}_i C_i$$

Where $n(t)$ is time dependent neutron numbers, $\boldsymbol{r}(t)$ reactivity, $\boldsymbol{b}_i$ the i^{th} delayed neutron fraction. A prompt neutron generation time, λ_i is i^{th} delayed neutron decay constant [2].

For a given power level, a small reactivity perturbation ($\boldsymbol{r}_e$), which is caused by daily refueling, Xe oscillation or reactivity variation in the vicinity of detectors, should be regulated and be stabilized by the RRS Controller H(S). The controller is designed to make the power deviation($\boldsymbol{D}n$) set to zero as possible . It is reasonable that we assume the reactor is linear, for LZC is feed-backing to the reactor with difference ($\boldsymbol{Dr}$) between perturbation ($\boldsymbol{r}_e$) and controlled reactivity ($\boldsymbol{r}$). The smaller perturbation production term ($\boldsymbol{Dr}\ \boldsymbol{D}n$) is neglected and the relationship in steady state makes two differential equations a simple transfer function. An input (small perturbation: $\boldsymbol{r}_e$) versus output (neutron power deviation: Δn) relationship is called a transfer function of the reactor. The positive feedback effect of reactivity in reactor, which is known to drift one of the poles of G(s) toward the

---

♣ Surveillance Requirements of Trip Parameters with respect to LOOP / END DEVICE / ANALYSIS response times for Wolsong 2/3/4 SDS1,SDS2,ECCS and Containment are specified in FSAR Chapter 7 (I&C), 14 (Commissioning Test), 15(Safety Analysis), 16 (Technical Spec.)

.

left half plane in s-domain, is negligible[3],[4]. The reactivity is too small to change the linearity of G(s)[5].

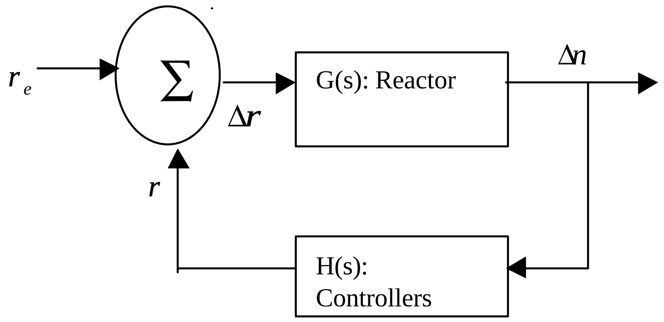

Figure 1. Block diagram of LZC and Reactors

$$G(s) = \frac{\Delta n}{\Delta r} = \frac{n_0}{s(A + \sum_{i=1}^{6} \frac{b_i}{1+l_i})} = n_0 \frac{\prod_{i=1}^{6}(s+l_i)}{s[A\prod_{i=1}^{6}(s+l_i) + \sum_{i=1}^{6}\prod_{i \neq j, j=1}^{6} b_i(1+l_i)]} \qquad \text{......(2)}$$

To take the neutron kinetics data from Wolsong 2/3/4 FSAR with equation (2), we get the transfer function shown in Table 1 with respect to poles, zeros and gains. Because there are no control bank requirements the adjuster rods are kept inserted during normal operation. The total reactivity range of LZC units is up to ±7mK. This is sufficient for controlling the refueling perturbations and for suppressing the Xenon oscillation [6].

Table 1. CANDU Reactors Transfer function with poles, zeros and gains.

Values of Poles and Zeros are negative: Located in **LHP**(Left Half Plane)

	Wolsong 1		Wolsong 2/3/4	
	Poles	Zeros	Poles	Zeros
1	0	-	0	-
2	0.053	0.0006	0.0054	0.0007
3	0.0728	0.0315	0.0708	0.0317
4	0.1999	0.1217	0.1957	0.1172
5	1.1911	0.3174	1.3789	0.3129
6	3.5692	1.3892	3.6684	1.4019
7	7.1670	3.7875	7.7732	3.9124
Gain	1118.57		1059.32	

2.2 LZC Controller Modeling

RRS for LZC has fast routine (bulk and spatial tilts control: 0.5 seconds) and slow routine (slow flux tilt control: 2 seconds). For fast reactivity control purpose, specified bulk control scheme is linearly modeled for this study.[7] Reactor Power Measurement and Calibration Routine(PMCR) is to measure the power from fast neutron detectors (in-core

Pt-clad detectors or Ion Chambers) and to calibrate with references sensing and calculating from various thermal power and slow neutron power. Then Demand Power Routine(DPR) is to calculate the effective power error (E_p) from measurement. $\boldsymbol{E_p}$ is driving command for control valves lift of LZC Absorbers. LZC units level is proportional to the reactivity which is confirmed with [0.072mk/ % level] during Commissioning Test for Wolsong units.

2.2.1 Power Measurement and Calibration Routine (PMCR) [8]

Input signals from measuring devices are pre-processed in PMCR and converted to controllers' inputs. They are one logarithmic bulk power, one logarithmic rate power and fourteen zone flux signal, which are shown in Figure 3. The PMCR gets two inputs from ion chamber amplifiers ($\boldsymbol{P_{IC}}$) and Pt-clad amplifiers($\boldsymbol{P_{LIN}}$). Mixed with two inputs according to the equation(3), it gives logarithmic power ($\boldsymbol{P_{LOG}}$) in decade units[9], [10].

$$P_{LOG} = (1 - a_P)(P_{IC})_{LOG} + a_P(P_{LIN})_{LOG} \qquad \text{...............................}(3)$$

Where a_P is the cross-over factor based on RTD thermal power, $\boldsymbol{(P_{IC})_{LOG}}$ the ion chamber logarithmic neutron power, $\boldsymbol{(P_{LIN})_{LOG}}$ the calibrated linear power based on 14 Pt-clad detectors, and $\boldsymbol{R_I}$ the median rate of logarithmic ion chamber power from the log-rate amlifiers. Crossover factor (a_P) is a function of RTD Thermal Power as shown in Figure 2.

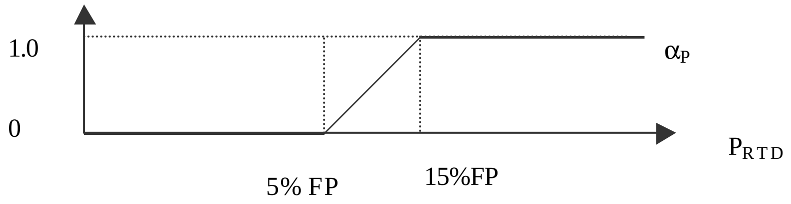

Figure 2. Crossover factor dependent on Thermal Power

Three ion chambers and fourteen pairs of platinum clad detectors are the primary measurement devices used for reactor bulk control, and are the only power measurement devices in the CANDU-6 RRS having sufficiently rapid response to provide stable regulation of the fission process. Unlike the ion chambers, which provide bulk power information only, the Pt-clad detectors supply flux tilts information as well. Above 0.15%FP, where flux tilt control is required, the Pt-clad detectors are the primary devices, not only for bulk control, but for the tilt control as well.

2.2.2 Demand Power Routines(DPR) [11]

For sensitivity study the log-power with time constants in ion chambers, Pt-clad detectors and their amplifier are not likely to be degraded or aging owing to dynamic calibration in PMCR. Two outputs of PMCR , P_{LOG} and R_I are compared with demand logarithmic power (P_{D_LOG}) and demand logarithmic rate of change (R_D) as following equation (4) in DPR with decade units.

$$E_P = K_B(P_{D\_LOG} - P_{D\_LOG}) - K_R(R_I - R_D) \qquad \text{.........................}(4)$$

For example, 101% is power converted into 0.0043 decade. If we assumed in equilibrium state at 100% power (P_{D_LOG}=1.0) and at no change of power (R_D =0), we can directly use E_P to actuate the reactivity control device. PMCR gives the rate of power change ($\boldsymbol{R_I}$) from a median of three outputs of ion chamber log-rate amplifiers. There is no calibration program on $\boldsymbol{R_I}$ while a dynamic bulk control calibration applies to the logarithmic power.

2.2.3 Liquid Zone Controller – Plant Modeling 12]

Including the PMCR and the DPR, we got a plant controller model as shown in Figure 4. The time constant of log-rate amplifiers is expressed as the first order lag (t_R) which can be degraded with aging. P_{LOG} can be corrected by dynamic calibration in PMCR if DCC executed properly during operation. However, R_I is not directly and dynamically calibrated in PMCR, for the fast PMCR reads median among signals (decades/second) of three log-rate amplifiers. It is an addition of lag term before the program gets input. The difference (E_p,:Effective Power Error) between the power deviation (with K_B gain) and the power change rate deviation (with K_R * s, derivative term and gain) is converted to LZC valves relative lift signal with K_p gain (R_{Lift}), shown in equation (4). All the control signals are converted by *Kc* conversion factor (0.0043 decades /%) from % full power to decade power inside the DCC program.

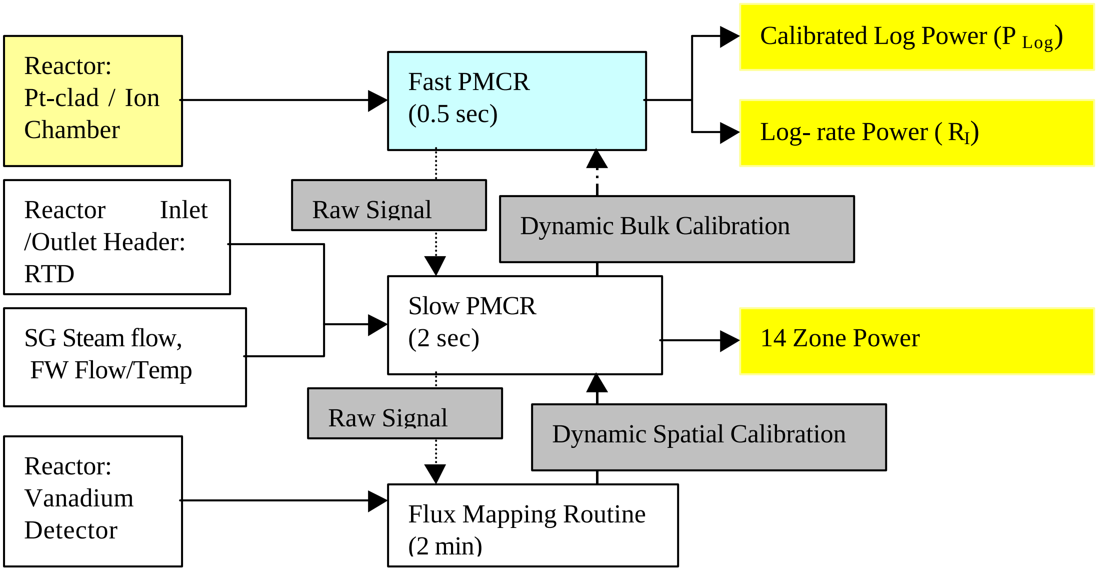

Figure 3. Power Measurement and Calibration DCC Software

Table 2. Controlled Variables in LZC Bulk Control

Symbol	***name***	***Symbol***	***name***
Dn	Neutron Power	*Dn*	Neutron Power
E_P	Effective Power Error	R_{Lift}	Relative LZC Valve Lift
B	Bias Valve Lift	*r*	Reactivity Absorbed by Tank Level

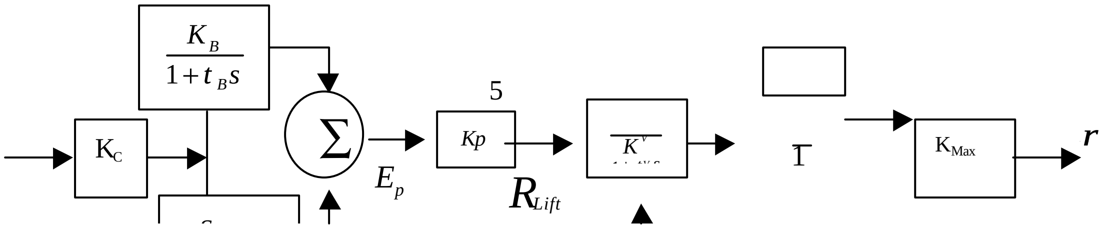

Figure 4. Block Diagram of LZC

The relative lift signal with the bias is converted into LZC tank level by the first order lag term (τ_V: valve time constant ($1/(1+\tau_V s)$) and the level tank integrate term ($1/s$). The block diagram of LZC controller is shown in Figure 4.

Table 3. Parameters’ Value in Wolsong Units LZC Model

Symbol	***Name***	***Values***
K_C	Conversion Factor	0.0043 Decades / %
τ_B	Time Constant of Linear Amplifier	0.05 Second
t_R	Time Constant of Log-rate Amplifier	0.75 Second
t_V	Time Constant of Valves	0.5 Second
K_B	Log Power Error Gain	1
K_R	Rate Log Power Gain	0.5
K_P	LZC Valves Relative Lift Gain	16 Units Lift / Decade
B	Bias Lift	0.5
K_V	LZC Valves Relative & Bias Lift to Flow	(1-2B(1-B))/(2B(1-B))
K_{MAX}	Maximum Reactivity Change	0.14e-3[mK/Second]

3. Modeling an adaptive controller using MRAS.

The model reference adaptive system (MRAS) was originally proposed to solve a problem in which the specification are given in terms of a reference model that tells how the process output ideally should response to the command signal. The regulator can be thought of as consisting of two loops: an inner loop, which is an ordinary feedback loop composed of the process, and the regulator. The parameters of the regulator are adjusted by the outer loop in such a way that the error e between the process output y and the model output y_m becomes small. The outer loop is thus also a regulator loop. The key problem is to determine the adjustment mechanism so that a stable system, which brings the error zero, is obtained.

3.1 The basic principle of MRAS 13]

The desired performance is expressed in terms of a reference model(MODEL), which gives the desired response to command signal. The system also has an ordinary feedback loop composed of the process and the regulator. The error ***e*** is the difference between the output of the plant and the reference model. The regulator (REG) has parameters that are changed based on the error. The inner loop provides the ordinary control loop feedback. The outer loop adjusts the parameters in the inner loop. The inner loop is assumed to be faster than the outer loop. Figure 5 is the original MRAS, or parallel MRAS proposed by Whitaker in 1958 [14], which is one of many possible ways of making a model reference system.

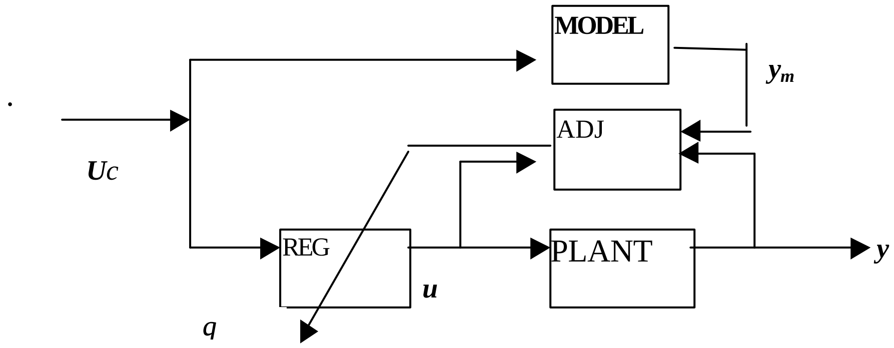

Figure 5. The orignal Model Reference Adaptive System

There are essentially three basic approaches to the analysis and design of MARS. The gradient method [13] is based on the assumption that the parameters change more slowly than the other variables in the system. This assumption, which admits a quasi-stationary treatment, is essential for the computation of the sensitivity derivatives that are needed in the adaptation mechanism. The gradient approach will not necessarily result in a stable closed-loop system. This observation inspired the application of stability theory Lyapnov' s stability theory and passivity theory has been used to modify the adaptation mechanism[15]. In all case, the rule for updating the parameters is of the form such as ;

$$\frac{dq}{dt} = -g\,j\,e \qquad . \ . \ . \ . \ (5)$$

In the gradient method the vector j is the negative gradient of the error with respect to the parameters. Estimation of the parameters or approximation may be needed to obtain the gradient. In other cases φ is a regression vector, which is found by filtering inputs, outputs, and command signals. The quantity ***e*** is the augmented error, which also can be interpreted as the prediction error of the estimation problem. It is customary to use an augmented error that is linear in the parameters. The gradient method is flexible and simple to any system structure. The calculations required are the determination of the sensitivity derivative.

Since the rule is based on a gradient calculation, it can immediately be asserted that the method will converge, provided that the adaptation gain γ is chosen sufficiently small. Further, the initial values of the parameters must be such that the closed loop system is stable. The method may be unstable if the adaptation gains are too high. The problem is that it is difficult to find the stability limits a priori.

3.2 The MIT Rule

The parameter adjustment scheme using the gradient approach is usually called the MIT rule. Assume that we attempt to change the parameters of the regulator so that the error (***e***) is driven to zero.

$$J(q) = \frac{e^2}{2} \qquad . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ (6)$$

Where *q* is the adjustable parameter, $e = y_m - y$. To make *J small* it is reasonable to change the parameter that determines the adaptation rate*(g)*. The derivative ($\varphi = \partial e/\partial\theta$) is the sensitivity derivative of the system. The *g* parameter determines the adaptation rate. The parameter adjustment mechanism (ADJ: $d\theta/dt$) can be regarded as composed of a linear filter for computing the sensitivity derivatives. The parameters are then introduced in the control law using a second multiplier. The MRAS attempts to adjust the parameters so that the correlation between the error ***e*** and the sensitivity derivative ($\partial e/\partial\theta$) becomes zero. The MIT rule will perform well if adaptation gain *g* is small. The allowable size depends, however, on the magnitude of the reference signal and the process gain. Consequently it is not possible to give fixed limits that guarantee stability. Modified adjustment rules can be obtain using stability theory. These rules are similar to MIT rule. The sensitivity derivatives are, however, replaced by other function.

$$\frac{dq}{dt} = -g \frac{j\, e}{a + j^T j} \qquad \text{. . . . . (7)}$$

where $\varphi = \partial e/\partial\theta$. It has been shown that the gradient approach will not necessarily give a stable closed-loop system. The approach taken was to derive an adjustment rule that appeared reasonable heuristically.

4. Simulation of the Model

4.1 Methods for simulation and an initial state

The calculation tolerance is set to 10^{-4} and step size is variably set by 10^{-2} to 10^{-5} for the accuracy and speed of calculation

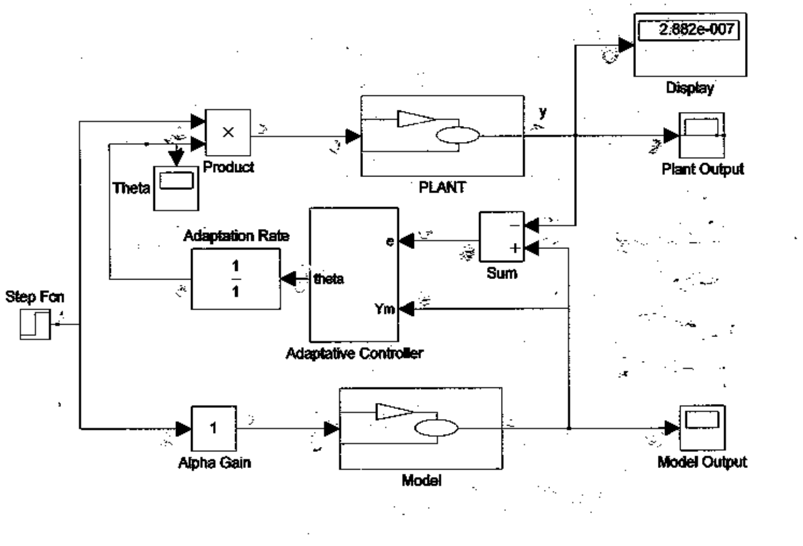

Figure 6. Block Diagram of Wolsong 2/3/4 adaptive RRS controller and plant

After constructing a transfer function of model reference, we simulated in time domain analysis to locate a sensitivity parameter with step function perturbation of a half magnitude of maximum reactivity change rate, 0.07mk for Wolsong Unit. It is a rationale that the control system can detect a half of its maximum through the digital input when a reactor disturbs with a maximum rate of change. The equilibrium State of reactor is 100 % FP with no reactivity change. The final block diagram of Adaptive RRS controller and plant used in simulation is shown Figure 6. It is t_V that we confirmed as the key parameters due to aging or improperly tuning. We solved the differential equation numerically with a Modified Euler Method.

4.2 Simulation of adaptive controller with design data of Wolsong

The step response of Figure 7 shows reference model and degraded plant with Wolsong design data and arbitrary t_V time constant setting . The time constant for reference model is 0.5 sec, and that for the plant 5.3 sec. After setting the g=–1, φ = y_m ,a =1**,** we get the stable dynamic response though the plant is undergoing in worst degraded case.

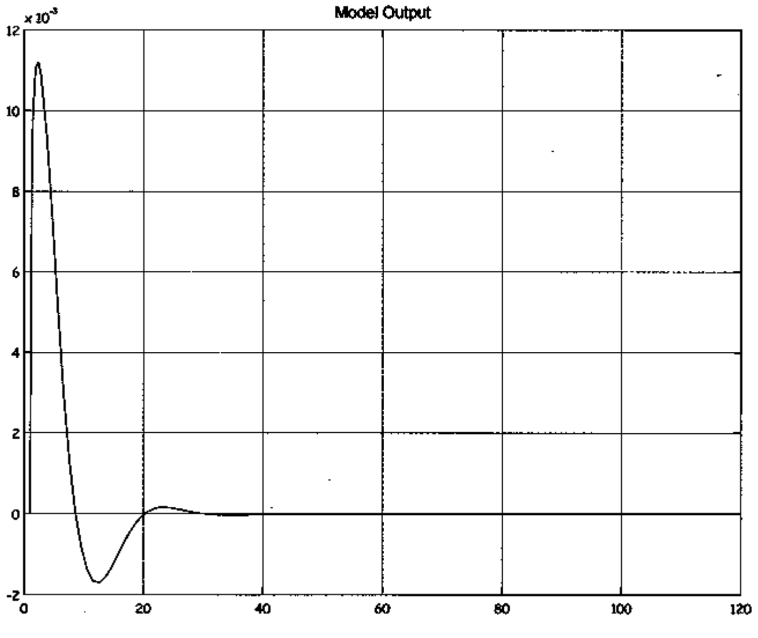

Figure 7-1 A perturbed response of reference model without MRAS and with MRAS

The reference model is designed such that all the design values of RRS are applied to it and that the time responses are identical both without MRAS and with MRAS

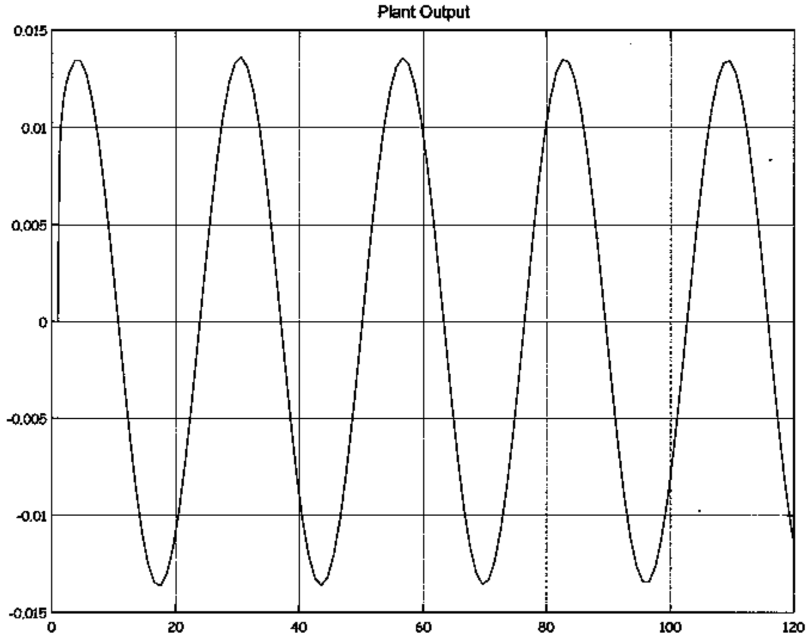

Figure 7-2 A perturbed response of response of degraded plant without MRAS

The plant is deliberately set such that all the design values of RRS are applied to it except the time constant of actuator, which is set 5.3 sec in lieu of 0.5 sec.

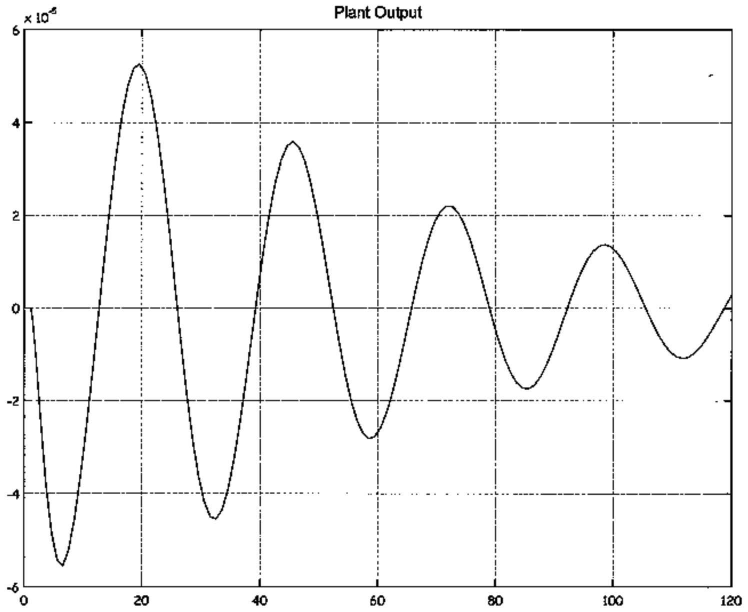

Figure 7-3 A perturbed response of response of degraded plant with MRAS

The plant is deliberately set such that all the design values of RRS are applied to it except the time constant of actuator, which is set 5.3 sec in lieu of 0.5 sec. The improved response shows that the adaptive control scheme performed well even though the adjustable gains - the adaptation rate and the model gain - is changed considerably. In simulation, the the adaptation rate =1 and the model gain=1.

5. Recommendations and Conclusion

We assumed that the RRS bulk control system had several weak points such as experiences of malfunctions of their controllers in Significant Event Reports. However we assured that the controller engineer should take into accounts to prevent these in-stability on design stage. Unfortunately we could not find any formal stability analysis study on process control system, which would prescribe the limitations and precautions when a plant is undergone commissioning, aging or degrading. We have analyzed the stability of bulk control of RRS within limited simulations and plant data with respect to changeable parameters.

There were findings during the inspection of the Wolsong Units.

(1) The response time of RRS controllers have not been measured since the RRS was commissioned.

(2) The fine tuning parameters and gains should have been justified with an analysis, but are tuned with experiences learned from previous CANDU plants.

With limited simulation results, we have confirmed that no fundamental barriers of RRS bulk control for Wolsong 2/3/4 exist.

(1) The dynamic calibration in DCC program continuously could correct a wrong input-sensing signal of log neutron power such like an adaptive control system.

(2) The gains for each CANDU plant seem to be suitably tuned during the commissioning with experiences from existing CANDU plants.

(3) The first order lag term of LZC valve is the most critical among other sensing and actuating devices. However it is a quite large degradation from design value.

(4) With a help of MRAS with in this study, the degraded controller with an aged actuator has a possibility to cope with the worst situation with which the DCC programs could not deal.

Consequently, it is necessary to extend this kind of stability study for confirmation or justification of tuning parameters or the lag term effects on the sensing and actuating devices. It will give a formal guidance for plant engineer when the tuning is necessary or preventive maintenance is planned against the aging effects. If the fault tolerant control scheme is applied, the operation of RRS will be relieved from such an unexpected malfunction.

References

1 . Oon-Pyo Zhu, ***A Survey and Evaluation of Stability-robustness of CANDU Reactor Regulating System***, KINS/ AR-573/97, December 1997.

2. Korea Electric Power Corporation, Wolsong 2/3/4 ***Final Safety Analysis Report*** Chapter4. Table 4.3-6, Neutron Kinetics Data for CANDU Reactor

3 . J.J Duderstadt, and L.J.Hamilton, ***Nuclear Reactor Analysis***, John Wiley & Sons, Inc., 1969

4. S.Gladstone and A. Seasonske, ***Nuclear Reactor Engineering***, 3rd Edition, Von Nostrand Reinhold Co.

5. M.A Schultz, ***Control of Nuclear Reactors and Power Plants***, McGraw Hill Book Company, 1961

6. Korea Electric Power Corporation, ***Wolsong 2/3/4 FSAR*** Chapter4. 4.3.2.5 Control Requirements and Reactivity Worth

---

7. AECL, Program Specification of ***Liquid Zone Control Absorbers***, 86-63729-PS-103,Rev.1, June 1996

8 . AECL, Program Specification, ***Reactor Power Measurement and Calibration Routine***, 86-63729-PS-101

9. AECL, Design Manual, ***Reactor Regulating In-Core Flux Detector System***, 86-63720-DM-002

10. AECL, Design Manual, ***Reactor Ion Chamber System***, 86-63720-DM-002

11 . AECL, Program Specification, ***Demand Power Routine***, 86-63729-PS-102

12 . AECL, Program Specification, ***Liquid Zone Controller Absorber***, 86-63729-PS-103

13 . K.J. Astrom and Bjorn Wittenmark, ***Adaptive Control***, Addison-Wesley Publishing Company , 1989

14 . P.V Osburn, H.P Whitaker and A. Kezer, ***New Developments in the Design of Adaptive Control Systems***, Paper, No. 61-39, 1nst. Aeronautical Sciences, Feb. 1961

15. Parks, P.C, ***Lyapnov Redesign of Model Reference Adaptive Control Systems***, IEEE Trans. AC-11, 365-365,1966