Validation of RRS Emulator against Pickering B Setback Event

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Abstract

This study compares the coupled RFSP IST/RRS Emulator response with a reactor setback at Pickering NGSB Unit 5. The RRS Emulator was adapted to model the behavior of the Pickering B RRS in the low power regime, where a log power signal is used. Good agreement between the station measurements and the simulation results has been achieved. The station measurements for the average zone level, power error and the control absorber insertion are well predicted by the *CERBERUS/RRS Emulator simulation.

1. Introduction

The overall function of the Reactor Regulating System (RRS) at Pickering NGS B is to control and monitor the core power magnitude and distribution. The specific aspects of this overall function are as follows:

- Reactor power measurement and calibration
- Demand power calculation
- Bulk (global) power control
- Spatial power control, i.e., spatial tilt mitigation
- Zone controller system response
- Reactivity device movement
- Poison addition
- Stepback and setback routine, etc.

The various functions of the RRS are executed over either a fast cycle interval Tf, a slow cycle Ts, or a very slow calibration cycle interval Tc, for recalculation of calibration factors. RRS also includes input sensors, the digital computer controller (DCC) programs, the reactivity control devices and associated display equipment. RRS maintains reactor power, when in the manual mode, at the setpoint Pset in the 'HOLDPOWER' submode.

The Pickering B reactor is equipped with four mechanical Control Absorbers (CA) to provide approximately 8.2 mk of additional reactivity. The CAs are essentially identical to shutoff rods. They are normally fully withdrawn, and can be driven in and out at constant speed, or can be dropped by de-energizing the electromagnetic clutches. The insertion time is 160 seconds when driving or 2.5 seconds when dropped by de-energizing the electromagnetic clutches. The clutches can be re-closed during a rod drop, resulting in a partial insertion of CA rods. The insertion or withdrawal of the CAs is controlled by the reactivity control program in the controlling computer. The drop of the rods is controlled by the stepback routine in both computers.

The CAs are arranged in two banks of two rods (CA01+CA04 and CA02+CA03) each. They are used as a coarse control override when the change in reactivity exceeds the rate or depth capability of the Liquid Zone Control (LZC) units. The number of pairs to be inserted is a function of average zone controller level and power error (see limit controller diagram in Figure 2). The power error is a function of measured reactor power, the current value of the demand power and the measured rate of power change. Depending upon the average zone level and power error, either one bank or both banks are driven into the core. If desired, the operator can select manual control of the control absorber drive.

The location of these absorbers is shown in Figure 1. The limit control diagram, Figure 2, defines the requirements for CA movements under Reactor Control System (RCS) control.

This study compares the coupled RFSP-IST/RRS Emulator response with a reactor setback at Pickering Unit 5. The Unit 5 setback event occurred on August 19, 2005. It resulted from degraded secondary side cooling due to algae plugging of the intake screens from Lake Ontario.

2. Methodology and Assumptions

2.1 RRS Emulator Code Modifications

The RRS Emulator was developed to emulate the RRS response and is based upon the SMOKIN RRS model [1]. The RRS Emulator is run in conjunction with the *CERBERUS module of RFSP-IST [2], which computes neutron fluxes in the core. Based upon these neutron fluxes, the RRS Emulator simulates the response of reactivity control devices. The coupling is performed using PhysicsShell [3].

This implementation, however, does not completely capture the design of the Pickering B RRS in the low power region. In particular, the switch-over from linear to log power below 13%FP is not captured. The switch-over from linear to log power is a feature of the Pickering B RRS that should be modelled since the reactor power in the station setback transient considered goes below 13%FP.

The switch-over from linear to log power was performed through modifications of the bulk power subroutine in the RRS Emulator package. These code additions switch the measured power used in the RRS Emulator from a true linear measured power to a scaled log power signal, which is given by

$$P_{LGSC} = 0.3454 P_{LOG} + 0.4346, \tag{1}$$

where P_{LOG} is the log power signal. The RRS Emulator derives power signals from in-core flux detectors. This was not changed as part of the modifications. The actual RRS design derives this signal directly from out-of-core ion chambers. For the purposes of this study, however, this approximation is reasonable as the ion chamber signals should be reasonably approximated by the average of the in-core flux detectors.

2.2 Assumptions

In a setback transient, it is assumed that the principle changes to core configuration will be in the CA insertion and Zone Controller Level. Other operational changes, such as xenon redistribution and fuel temperature change, have not been accounted for. Due to the relatively short time for a reactor setback to complete (on the order of minutes), the I/Xe-135 transient is ignored.

It is assumed that throughout the transient, the thermalhydraulic conditions remain unchanged. During the reactor setback transient, the reduction in channel power will reduce the enthalpy rise across the fuel channel. After a reactor setback completes power reduction to 2%FP, the average coolant temperature is reduced from the full power best estimate value of 273.15 °C to the hot shutdown value of 269.55 °C. The coolant density increases from 845.99 kg/m3 to 854.99 kg/m3. The associated change in reactivity is small and will be neglected in these simulations.

The best estimate assumptions summarized in Table 1 are assumed to apply. However the moderator temperature was altered from 65 °C to 61 °C based upon conditions at the station when this transient occurred. The positive reactivity due to the change in fuel temperature is also neglected in this study. The best estimate, full power fuel temperature will be assumed throughout the setback transients simulated in this study. This is done to simplify the analysis.

3. Results

The power maneuver for the setback transient can be seen in Figure 3. The rate of power reduction is 0.6%FP/s. A typical setback transient would proceed to reduce power to 2%FP. The primary focus of this study was to determine if the control absorber insertion during the initial ramp down could be predicted by the RRS Emulator. The subsequent portions of the transient where the power holds at 10%FP before finally reducing to 2%FP was not the primary concern of this analysis. In order to simulate the whole transient, the power hold at 10%FP was modelled approximately by holding the setpoint power in the simulations at 10%FP for a short duration, after which the setpoint power is reduced again to 2%FP.

Figure 3 shows a comparison between the simulated reactor power and the Unit 5 measured power. The two signals compare well, with deviations emerging around the approach to the power hold at 10%FP. This results in the simulated power slightly decreasing below 10%FP before rising back to 10%FP as negative reactivity is withdrawn from the core.

Figure 4 shows the comparison between simulated power error and the station power error measurement. The power error is computed as the sum of a proportional and rate term. The proportional term is the difference between the current reactor power and the demand power. The demand power is gradually reduced through the course of the transient to match the power maneuvering rate. The rate term in the power error calculation is proportional to the rate of change of power.

For most of the transient, the two power errors are in good agreement, as shown in Figure 4. This is especially true when the power error is positive. The negative power error in the simulation results is slightly over-predicted. This occurs once the power has been reduced to the value of 10%FP. The negative power error, however, is large enough in the simulation to cause withdrawal of adjusters. It should be noted that these deviations are immaterial when assessing the effectiveness of reactor setback under different postulated operational conditions. Such studies require a good agreement between the magnitudes of the simulated and measured positive power errors, as is evident in Figure 4. The primary focus of this study was to determine if during the initial ramp down in power, the control absorber insertions could be simulated by the RRS Emulator.

Figure 5 shows the comparison between the simulated and measured average zone levels. The maximum deviation occurs near the end of the transient where the simulation fails to capture the third rise in average zone level, and subsequent decrease in the average zone level. By this point in the transient, however, a good agreement between the simulated and measured results is not expected. Since the over-prediction of the negative power error earlier in the transient resulted in the withdrawal of adjusters in addition to CAs, some of the negative reactivity added in the station transient due to a rise in average zone level can be accounted for by insertion of adjusters back into the core. For even later times in the transient, negative reactivity due to Xenon build-up will not be captured in the simplified methodology used in this analysis, where core burning is not modeled during the setback transient. It is evident from the reasonably good comparison for the majority of the simulation that the Xenon reactivity effects are not dominant.

Figure 6 shows the comparison between the simulated and measured control absorber insertions. The control absorber insertion is well-predicted for the first ramp down to 10%FP. In both the simulated and measured data, the CA insertion is initiated almost at the same time. A slight insertion of the second CA bank was predicted during the first insertion of CA rods, which commences just prior to 180s. This can be seen to be the result of the crossing of the two bank insertion line on the limit controller diagram in the simulation. This can be seen by comparing the diamond marker in Figure 7 and Figure 8, which plot the limit controller phase space diagram for the measured and simulated station setback transients, respectively. Figure 7 indicates that the average zone level and power error place the system very close to the two bank insertion line of the limit controller diagram for the actual station setback (see diamond in the figure). Figure 8 shows that the average zone level and power error for the simulated station setback transient place the system slightly over the two bank insertion line (see diamond in the figure). The slight insertion of the second bank in the simulated station transient is due to the marginal crossing of the two bank insertion threshold. This deviation from the actual station setback is, however, not due to a gross difference in predicted RRS behaviour with the true station RRS behaviour.

Following the initial insertion of control absorbers, good agreement between station measurements and simulation is not achieved. The larger magnitude of the negative power error in the simulation leads to adjuster withdrawal in the simulation that is not seen in the station data. This can be seen in Figure 7 and Figure 8, which represent the limit controller phase space diagram. The inner locus of points in Figure 7 can be seen to never cross the line for adjuster insertion, whereas the inner locus of points in Figure 8 does cross the line for adjuster insertion. The intent of this study was to assess the insertion of control absorbers during the initial power ramp down to a low power level. No further fine-tuning was therefore performed to attain better results between measured data and simulation for this later stage of the transient.

4. Summary

This study makes use of reactor kinetics simulations that involve the coupling of the RRS Emulator with the RFSP-IST *CERBERUS module.

Good agreement between the station measurements and the simulation results has been achieved for the initial power ramp down. In particular, the station measurements for the average zone level, power error and the CA insertion are well-predicted by the *CERBERUS/RRS Emulator simulation. Deviations occur due to small disagreements between the simulation results and station measurements for the power error and average zone level. These small deviations cause a slight insertion of the second CA bank in the simulation when no insertion occurred at the station. These results obtained from the *CERBERUS/RRS Emulator simulation provide support for the application of this methodology to the modelling of RRS response. Additional fine-tuning of the RRS Emulator would, however, be required to provide a more accurate prediction of the power error.

5. References

[1] M.Z. Farooqui and M.B. Gold, "CANDU Reactor Regulating System Response Modelling in SMOKIN Code", Third International Conference on Simulation Methods in Nuclear Engineering, Montreal Canada, April 18-20, 1990.

[2] B. Rouben, "RFSP-IST, The Industry Standard Tool Computer Program for CANDU Reactor Core Design and Analysis", Proceedings of the 13th Pacific Basin Nuclear Conference, Shenzhen, China, Oct. 21-25, 2002.

[3] J. Szymandera, L. Blake, B. G. Phan and O. Nainer, "PhysicsShell: A Solution to Multi-Code Linking", CNS 2008 Symposium on Simulation Methods in Nuclear Engineering, Nov. 2-4, 2008.

Table 1 – Best Estimate Analysis Assumptions

Parameter	Value
Coolant Purity	97.93 at%
Moderator Temperature	65.0 °C
Moderator Purity	99.88 at%
Moderator Gadolinium Concentration	0 ppm
Moderator Boron Concentration	0 ppm
Average Coolant Density	845.99 kg/m^3
Average Coolant Temperature	273.15 °C
Liquid Zone Levels	Adjusted to achieve an initial flux tilt of 1.84%
Power	1661.2 MW
Fraction of Full Power	1.0
Thermal/Fission Power Ratio	0.9525
Neutron Velocities	(fast) 9.277×10^6 cm/s (slow) 0.2794×10^6 cm/s
Reactivity Device Worth	In BEAU methodology (cases), SOR worth decreased by 6%; this decrement was not applied to CA rods in this study*.

*Control absorbers are identical to that of (long) shutoff rods. Hence, a similar decrement is also expected in their reactivity worth. This small change is not expected to have any effect on the availability of the RRS setback routine, although a slightly greater insertion of CAs would occur.

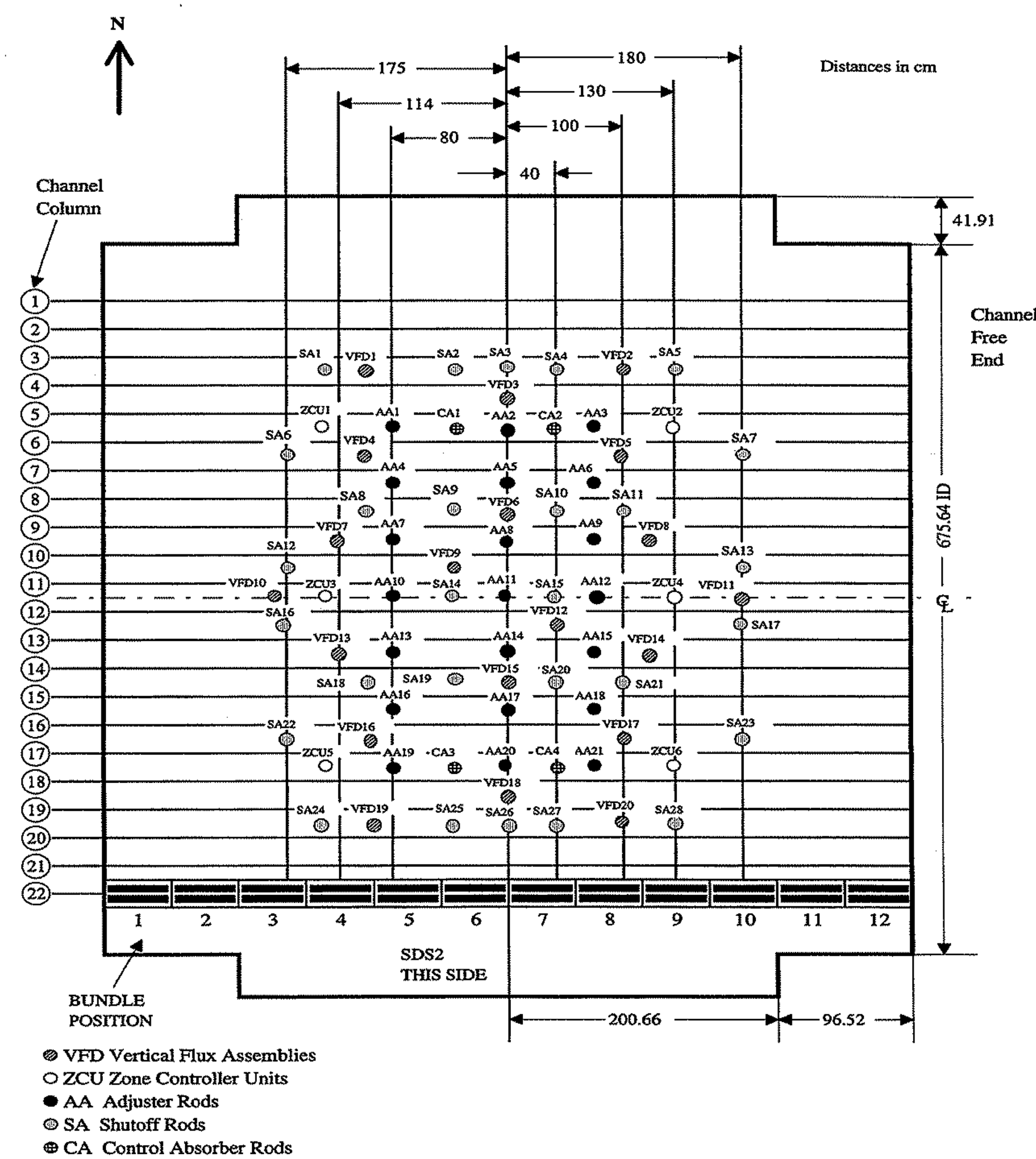

Figure 1 – Location of Vertical Reactivity control Units

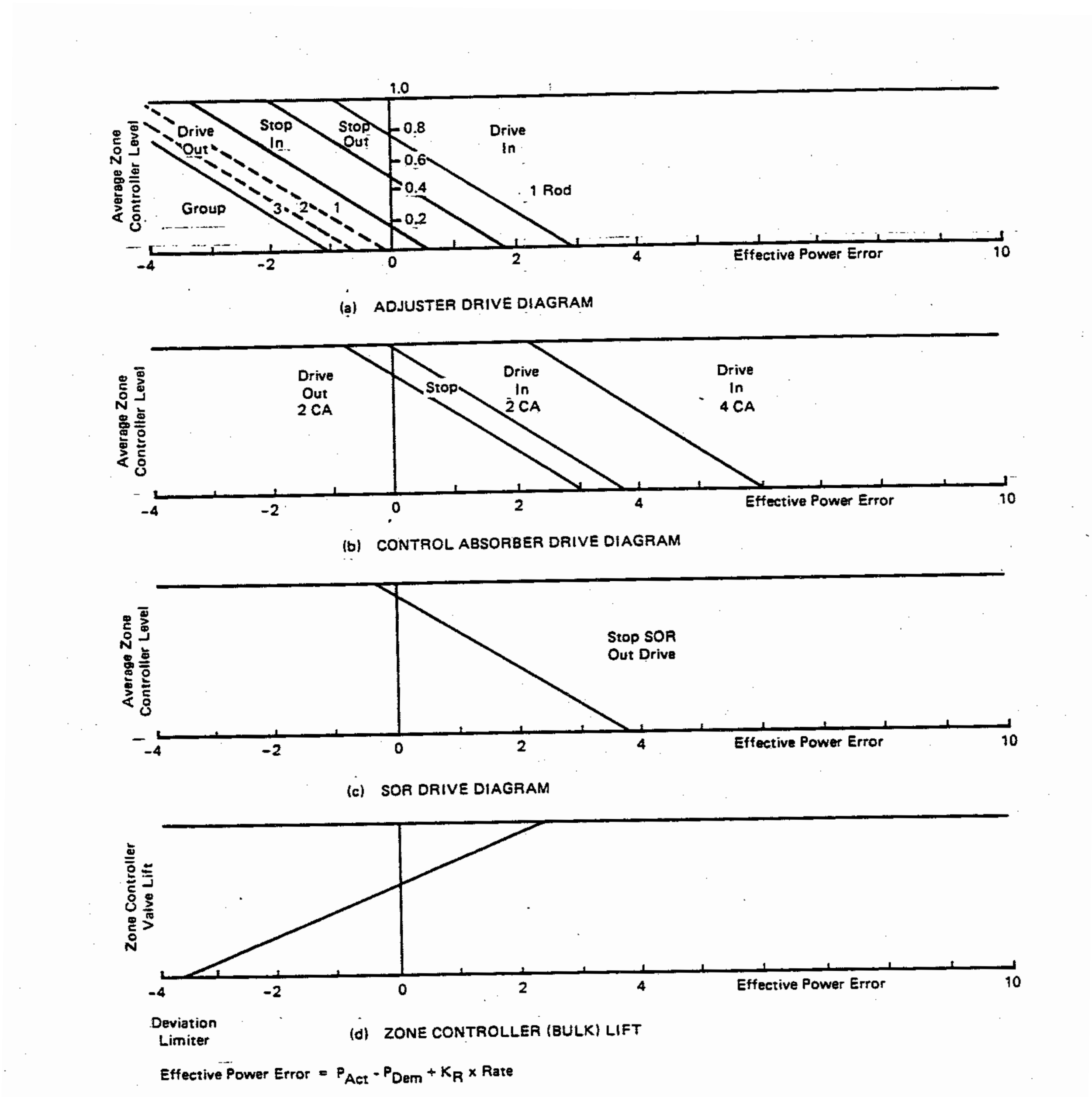

Figure 2 – Pickering B Limit Controller Diagram

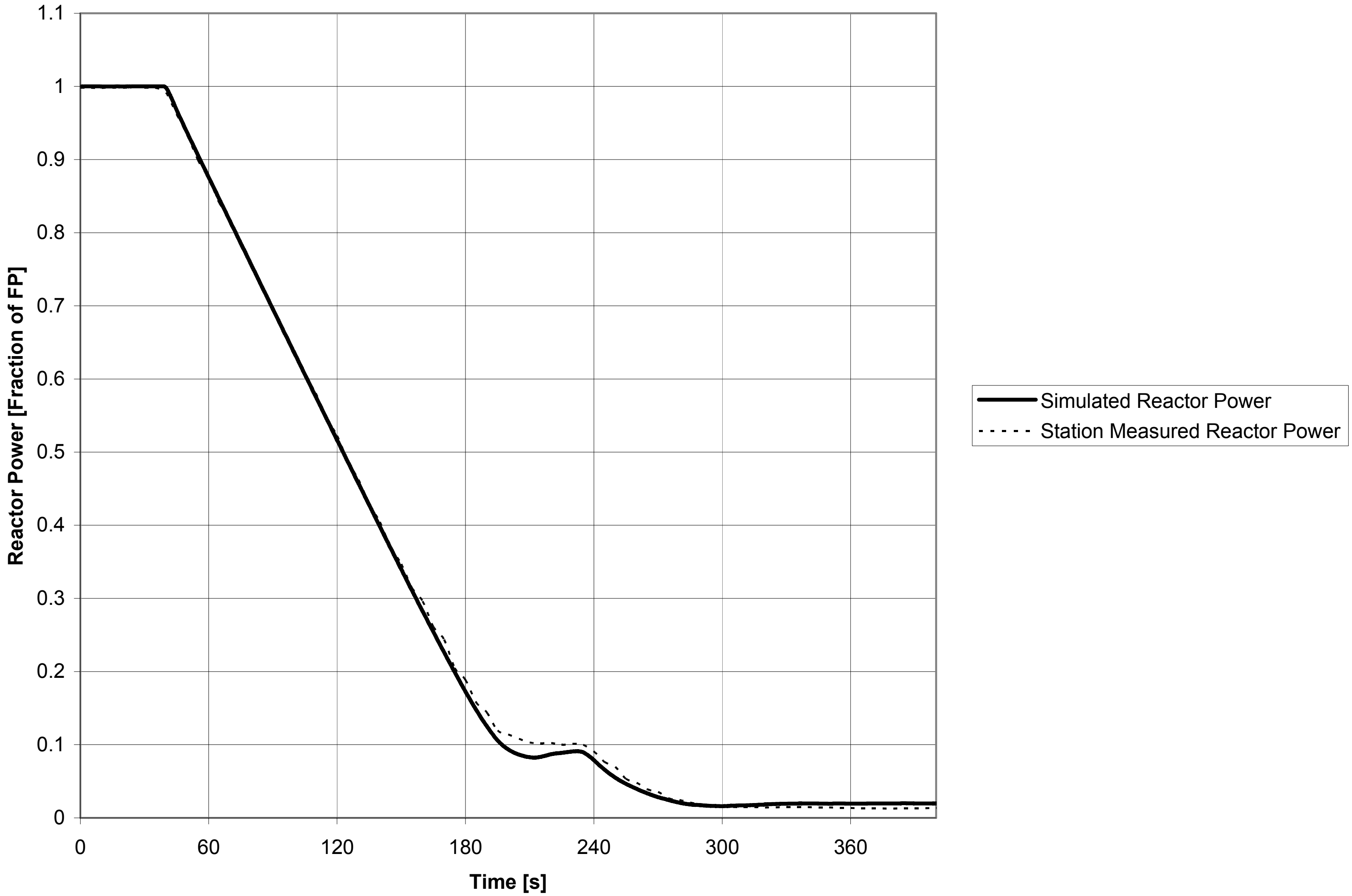

Figure 3 – Comparison between Simulated Reactor Neutronic Power and PNGSB Unit 5 Measured Reactor Neutronic Power

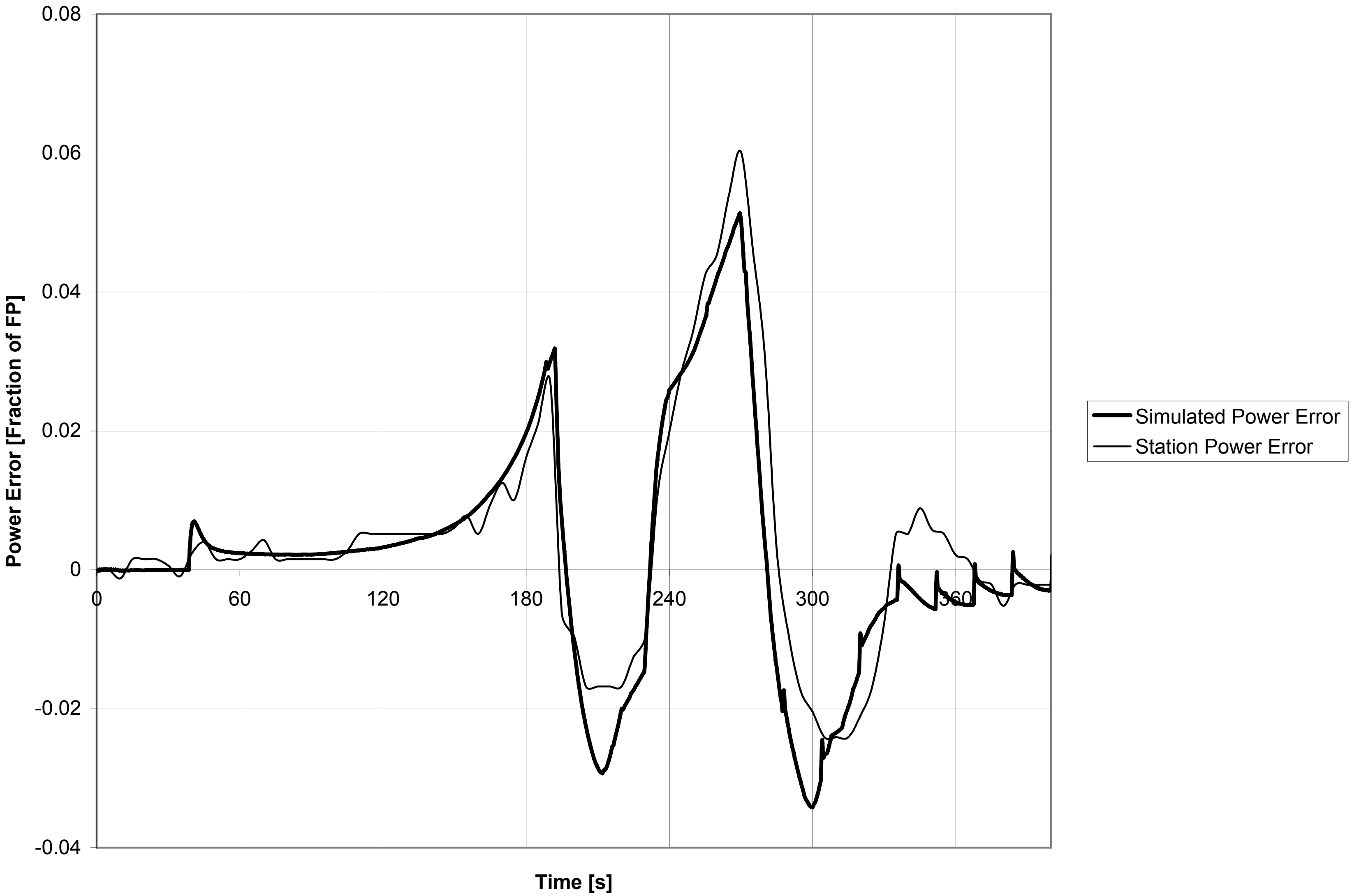

Figure 4 – Comparison between Simulated Power Error and PNGSB Unit 5 Measured Power Error

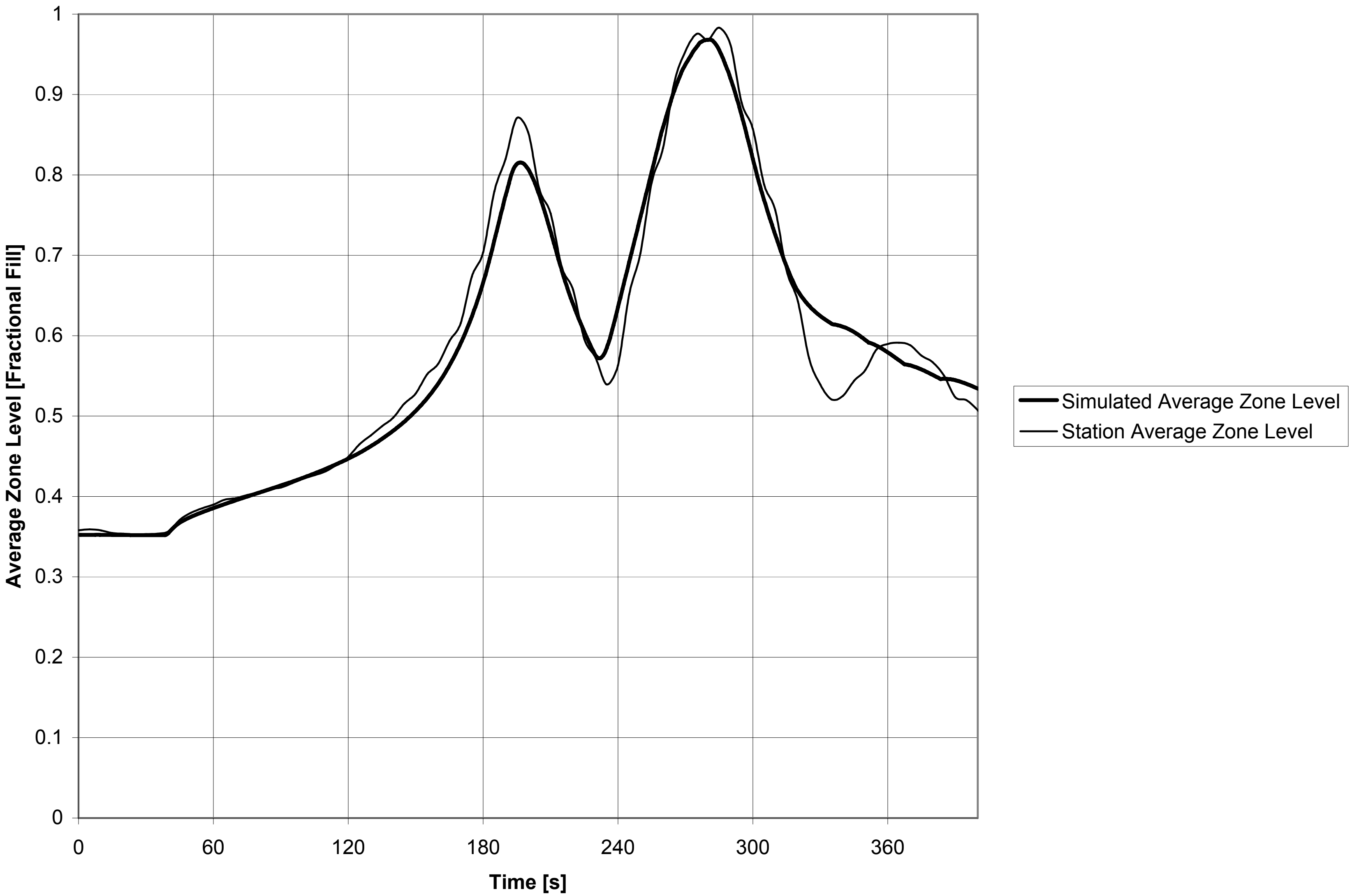

Figure 5 – Comparison between Simulated Average Zone Level and PNGSB Unit 5 Measured Average Zone Level

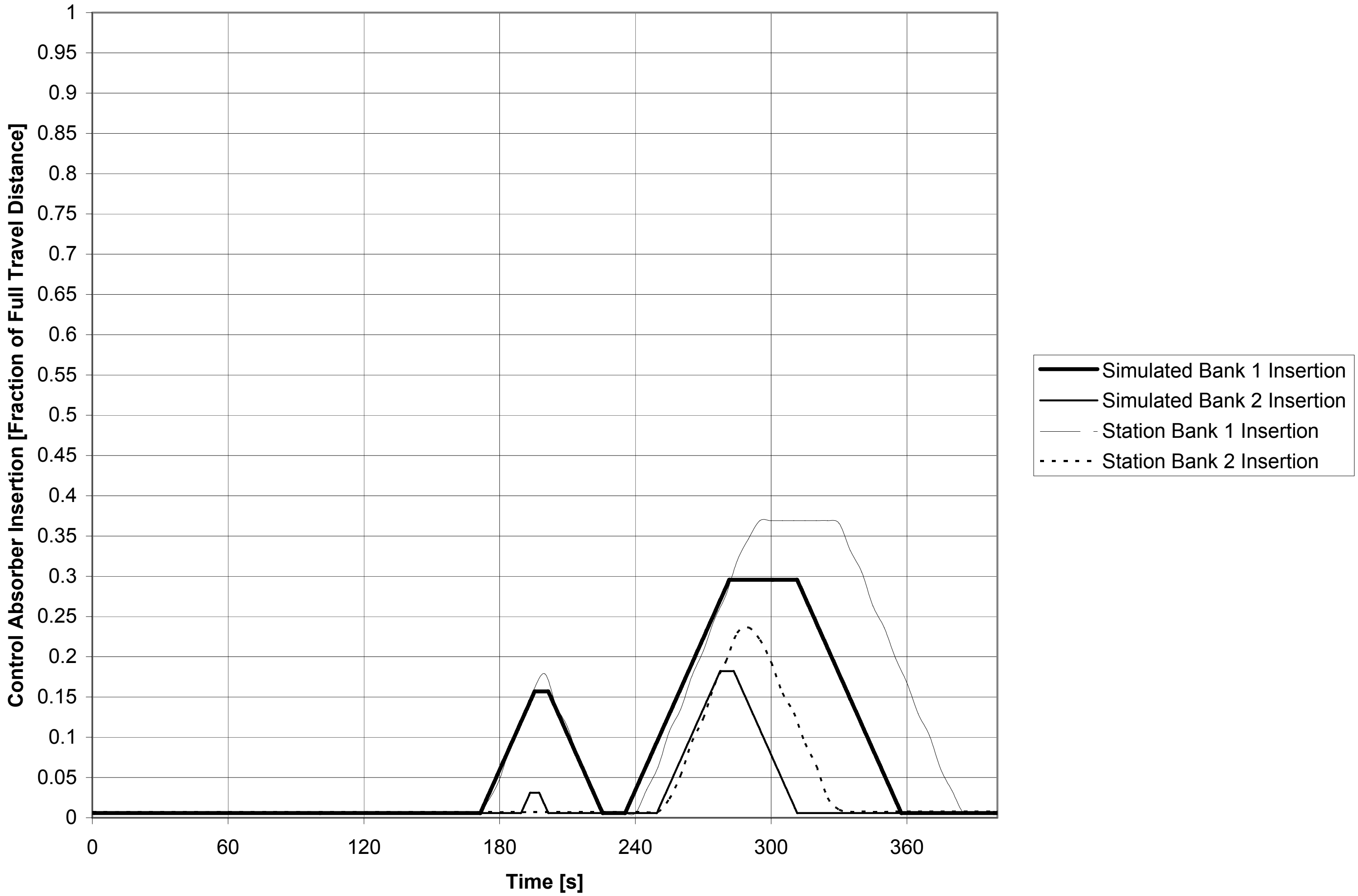

Figure 6 – Comparison between Simulated Control Absorber Insertion and PNGSB Unit 5 Measured Control Absorber Insertion

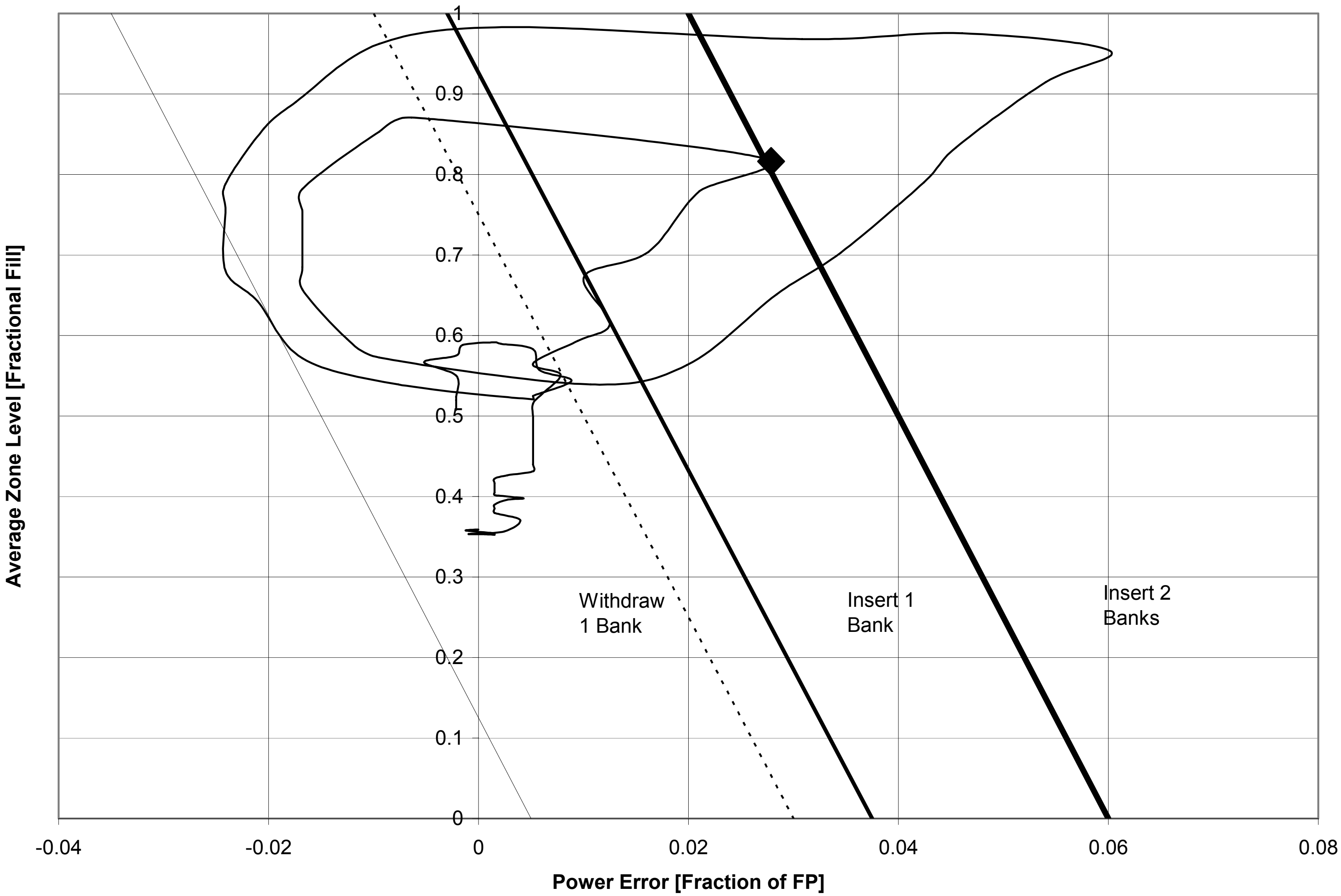

Figure 7 – PNGSB Unit 5 Station Setback Transient Limit Controller Diagram

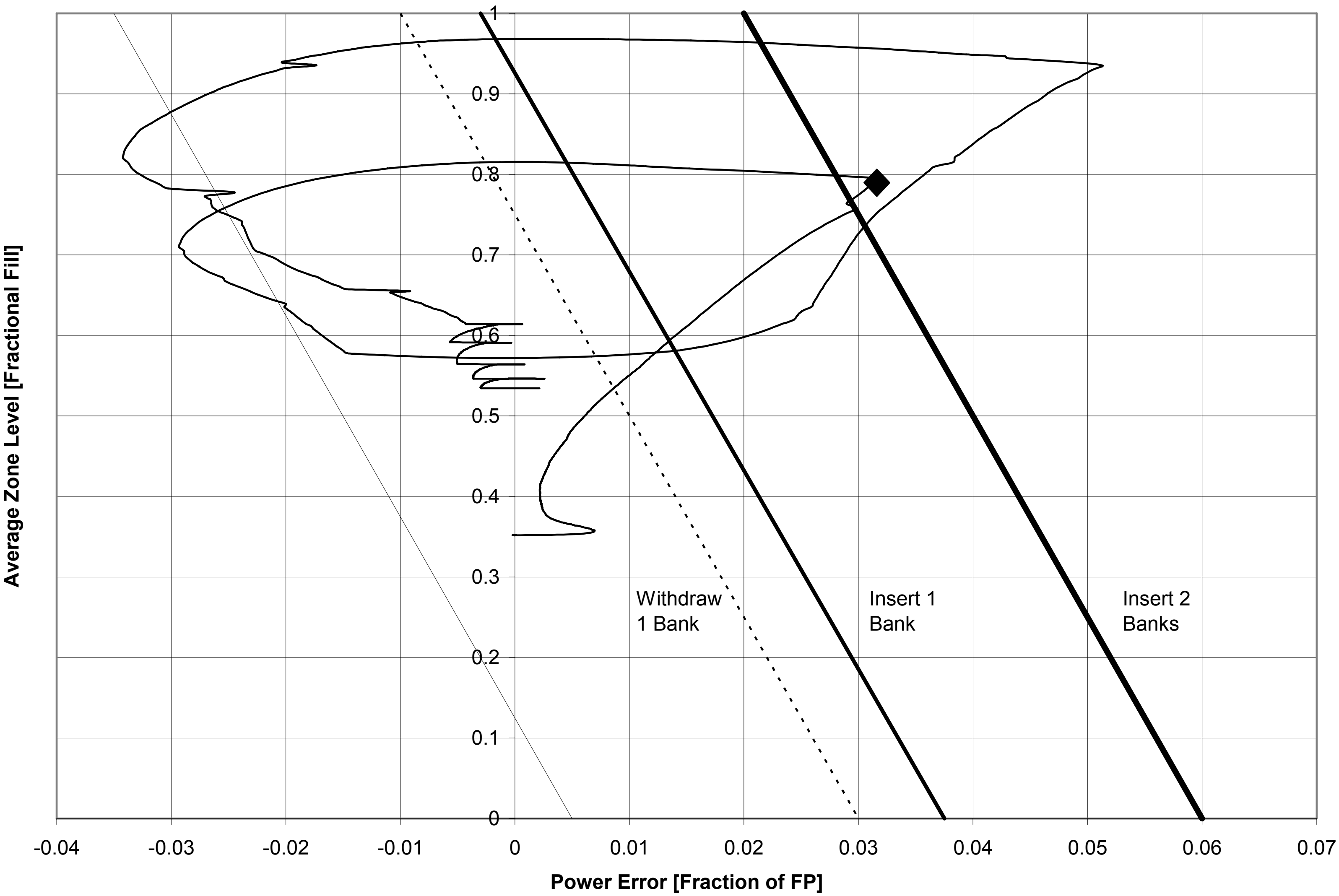

Figure 8 – Simulated Station Transient Limit Controller Diagram