Robust Model-Based Steam Generator Level Control in Nuclear Power Plant

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Abstract

Economic feasibility of a power plant requires smooth and uninterrupted plant operation in the face of varying electrical power demand. The feed-water system in a power plant is a major contributor to plant unavailability. The purpose of this paper is to present a general framework for addressing all aspects of this problem and design, analyze and evaluate a water level controller for Steam Generator (SG) and using robust controller design procedure, Linear Quadratic Gaussian with Loop Transfer Recovery, LQG/LTR for low power and high power range. Simulations show that the proposed controller improves transient response of (SG) water level and demonstrate its superiority to existing conventional PI controllers.

1. Introduction

Next generation of new Nuclear Power Plants need to employ robust controls and higher level of automation and fault tolerance system to increase availability, reliability, precise control, reduce accident risk, and lower operating costs. In today's competitive power market, control systems play a vital role in the operation and performance and helping plants meet efficiency, reliability, emissions goals of Nuclear Power Plants. The Steam Generator (SG) in a nuclear power plant plays an important role in cooling the reactor and producing steam for the turbine-generator. An evaluation of reactor trip data has shown that the Feed-Water System is the major contributor to automatic reactor and turbine trips. Many advanced methods have been suggested to resolve the SG water level control problems. For example Irving et al. presented a linear model with varying parameters to describe the U-tube steam generator (UTSG) dynamics over the entire operating power range. Then they proposed a model reference adaptive PID controller [2]. Design of suboptimal controller using linear output feedback control has been reported by Feliachi and Belbelidia [4]. Choi et al. proposed a PI-type controller that uses an observer to estimate the UTSG water inventory [5]. Na and No designed an adaptive observer-based controller [6] and Na presented a UTSG water level controller based on the estimation of flow errors [7].

Steam Generator level control in Nuclear Power Plants is critical for both plant protection and equipment safety. The proper water level control of a nuclear steam generator is of a great importance in order to secure the sufficient cooling source of the nuclear reactor and to prevent the damage of turbine blades. Stabilizing water level of the steam generator in Nuclear Power Plant is a very important problem since (SG) shows complicated dynamic behaviours with nonlinear characteristics, non-minimum phase phenomenon and multi input multi output system. The swell and shrink effect is one of main factors for frequent forced outage of the Nuclear Power Plants. Large level and power oscillation at low power operation also is another major problem with existing (SG) Water Level Control strategy in Nuclear Power Plants. There is need to investigate these problems and systematically design a controller for Steam Generator (SG) Water Level Control. For the Steam Generator (SG) in a nuclear power plant, the main goal of its control system is to maintain the SG water level at a desired value by regulating the feed-water flow rate. The water level of the steam generator must not be allowed to rise too high. An increase in this level may interfere with the process of separating moisture from steam within the reducing Steam Generator and Turbine efficiency and carrying moisture and impurities into the process or Turbine. Also, the low water level should be prevented. A dramatic decrease in this level may uncover the Steam Generator tubes, allowing them to become overheated and damaged. Therefore, the control of the SG water level is important to determine power plant responses in the event of changes in the operating load.

2. The water level control problems and Steam Generator (SG) Model

Currently, constant-gain PI has been used for SG level control, owing to the easy control algorithm and the advantage which have been proven on the nuclear power plant. However, since there are problems with stability control during low power operation (less than 20% of the nominal power) and start-up, at low power operations water level can't be maintained properly with PI controller due to the thermal effects of SG and normally level control is performed manually at low powers and only a highly experienced operator can operate during low power operation. A great deal of time and an expensive simulator is needed for the training of an operator. Even with a skilled team of operators, the rate of incidents due to manual control could not be neglected. Therefore, development and upgrading SG level control strategy in Nuclear Power Plants is very important.

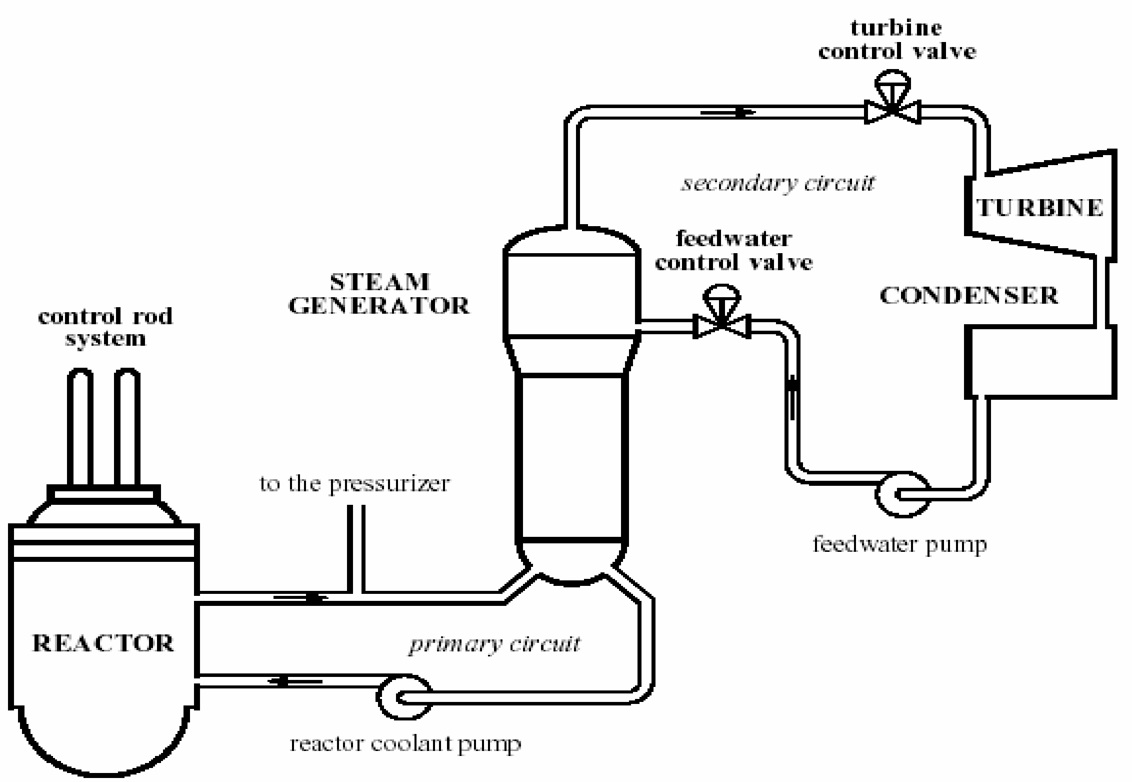


Fig. 1. General view of a Nuclear Power Plant and schematic of a (SG).

The difficulties in designing an effective level control system for the steam generator arise from a number of factors: (1) the inverse response behaviour of the plant, particularly at low operating power due to the so-called "swell and shrink" effects and big difference between water inlet and steam outlet temperatures; (2) variation of plant dynamics with operating power; (3) unreliable flow measurements at low power which preclude effective use of feed-forward control.

Some theoretical models based on thermodynamic experiments and/or energy conservative equations have been developed to use for operator training simulator and accident analysis and so on. The controller design and the resulting controller performance on the actual plant are both strongly dependent on the accuracy of the mathematical model used to describe the plant. However, a highly accurate model is generally also highly complex and nonlinear, and therefore leads to difficulties in controller design. For the purpose of controller design, the model should be simple and at the same time relatively accurate in describing the principal dynamics of the Steam Generator. In this study we use the model which has been widely used by many researchers for control purposes presented by Irving et al. [2].

The model is a linear fourth-order model whose parameters depend on reactor power level. The transfer function relating the feed-water flow-rate and the steam flow-rate to the water level is given by,

$$Y(s) = \frac{G_1}{S} \times (q_w(s) - q_v(s)) - \frac{G_2}{(1+\tau_2 S)} \times (q_w(s) - q_v(s))$$

$$+ \frac{G_3}{\tau_1{}^{-2} + 4\pi^2 T^2 + 2\tau_1{}^{-2} S + S^2} \times q_w(s) \tag{1}$$

where,

$Y(s), q_w(s)$ and $q_v(s)$ are narrow range water level, feed-water flow-rate, and steam flow-rate respectively, τ_1, τ_2 and T are damping time constants and oscillation period respectively.

$\frac{G_1}{S}$ is the mass capacity effect of the SG. It integrates the flow difference to calculate the change in water level. This term accounts for the level change due to feed water inlet to steam generator and the steam outlet from it. This quantity means the actual water capacity which critically affects the removal capability of the primary heat. G_1 is positive constant and does not depend on load.

$-\frac{G_2}{(1+\tau_2 S)}$ is the thermal negative effect caused by "swell and shrink". Since these phenomena exhibit exponential responses for step changes of the feed water flow-rate and the steam flow-rate, they are described by a first-order equation. G_2 is positive and dependent on load. As load increases G_2 decreases. The last term is the mechanical oscillation effect caused by the inflow of the feed-water to the SG. This is a mechanical oscillation term due to momentum of the water in the downcomer. The variable G_3 is positive.

All the water removed from the steam is returned to the downcomer and is recirculated. The recirculating water has large momentum acting against relatively small flow-rate changes. When the feed-water flow-rate is suddenly decreased, the water level in the downcomer falls initially and then begins to oscillate. This is due to the momentum of the water in the downcomer keeping the recirculating flow going down initially and then slowing down. The mechanical oscillation disappears completely after a small multiple of the damping time constant. We divide the steam generator dynamics into four linearized regions with respect to operating power level and assume that the dynamics vary linearly over these regions. These variations of the plant parameters with respect to power level are presented in the graphical form. The actual plant parameters may vary differently, so we study the performance of the controller under the situations when the parameter drifts from what is projected by linear interpolation. Systematic approaches such as LQR method is used to derive the control law where some objectives functions are minimized to derive an optimal controller. The main objective of the controller is to maintain the water level in the steam generator under various operating levels. We also show the effect of parameter drift on the water level through computer simulation results. To design the proposed controller we transform the plant dynamics into a suitable state-space form.

The state equations are defined as follows:

$$\begin{aligned}
\delta\dot{x}_1(t) &= \mathrm{G}_1(\delta q_w(t) - \delta q_v(t)) \\
\delta\dot{x}_2(t) &= -\tau_2^{-1}\delta x_2(t) - \frac{G_2}{\tau_2} \times (\delta q_w(t) - \delta q_v(t)) \\
\delta\dot{x}_3(t) &= -2\tau_1^{-1}\delta x_3(t) + \delta x_4 + G_3\delta q_w(t) \\
\delta\dot{x}_4(t) &= -(\tau_1^{-2} + 4\pi^2 T^{-2})\delta x_3(t)
\end{aligned} \tag{2}$$

and the output (water level) is

$$\delta y_p(t) = \delta x_1(t) + \delta x_2(t) + \delta x_3(t)$$

If we define $\delta x_p(t) \triangleq [\delta\ x_1 \quad \delta x_2 \quad \delta x_3 \quad \delta x_4]^T$, the dynamics of the steam generator system can then be reduced to the following state-space equations:

$$\delta\dot{x}_p(t) = A_p\,\delta x_p(t) + B_p\,\delta q_w(t) + F_p\,\delta q_V(t) \tag{3}$$

$$\delta y_p(t) = C_P \delta x_p(t)$$

where *Ap*, *Bp*, and *Cp* matrices are given as:

$$A_p = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & a_{22} & 0 & 0 \\ 0 & 0 & a_{33} & a_{34} \\ 0 & 0 & a_{43} & 0 \end{bmatrix}, \quad B_p = \begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ 0 \end{bmatrix}, \quad F_p = \begin{bmatrix} d_1 \\ d_2 \\ 0 \\ 0 \end{bmatrix}, \quad C_P = \begin{bmatrix} 1 & 1 & 1 & 0 \end{bmatrix} \tag{4}$$

where,

$$a_{22} = -\tau_2^{-1}, a_{33} = -2\tau_1^{-1}, \; a_{34} = 1, \; a_{43} = -(\tau_1^{-2} + 4\pi^2 T^{-2}), \; b_1 = G_1, \; b_2 = -G_2\tau_2^{-1}, \; b_3 = G_3, \quad d_1 = -G_1,$$

$$d_2 = \frac{G_2}{\tau_2}. \tag{5}$$

The approximate linearized model can be given by,

$$\delta \dot{x}_p(t) = A_0 \delta x_p(t) + B_0 \delta u_P(t) + F_0 \delta w(t) \tag{6}$$

$$\delta y_p(t) = C_0 \delta x_p(t)$$

Where $\delta u_P(t) \triangleq \delta q_w(t)$ and $\delta w(t) \triangleq \delta q_v(t)$

In the subsequent derivations δs will be removed for clarity. We will write the System equations as:

$$\dot{x}_p(t) = A_0 x_p(t) + B_0 u_P(t) + F_0 w(t) \tag{7}$$

$$y_p(t) = C_0 x_p(t)$$

Where x_p, q_v, q_w and y_p are the variations in plant state, feed-water flow-rate, steam flow-rate, and the system output. One of the objectives is to design a state feedback controller so that the system is internally stable and its output (actual water level) asymptotically tracks the reference input (desired water level). This output tracking is achieved using a dynamic compensator through the introduction of a vector q defined below:

$$\dot{q} = y_P - y_r = C_0 x_p - y_r \tag{8}$$

Where, y_r is the reference input.

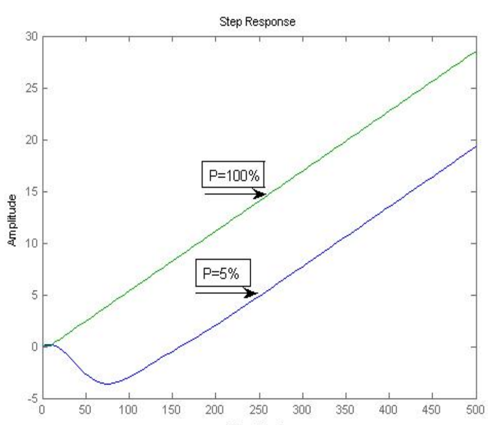
The state-space equations for the augmented system may be given by,

$$\dot{x}_{pq}(t) = A_{pq} x_{pq}(t) + B_{pq} u_{Pq}(t) + F_{pq} w(t) + H_{pq} y_r$$

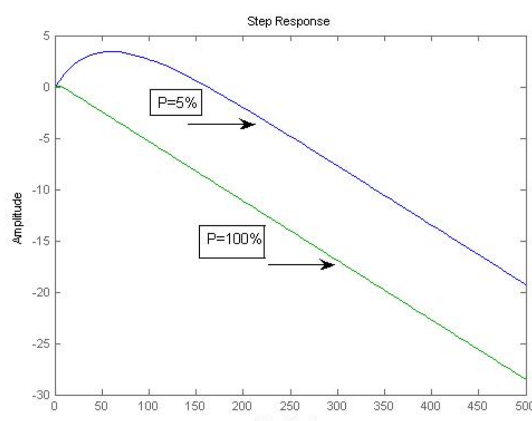
$$y_{pq}(t) = C_{pq} x_{pq}(t) \tag{9}$$

Where, $x_{pq} = [x_p \quad q]^T$, $y_{pq} = y_p$ and

$$A_{pq} = \begin{bmatrix} A_0 & 0 \\ C_0 & 0 \end{bmatrix},\ B_{pq} = \begin{bmatrix} B_0 \\ 0 \end{bmatrix},\ C_{pq} = \begin{bmatrix} C_0 & 0 \end{bmatrix},\ F_{pq} = \begin{bmatrix} F_0 \\ 0 \end{bmatrix},\ H_{pq} = \begin{bmatrix} 0 \\ -1 \end{bmatrix} \tag{10}$$



(a)



(b)

Figure 2. Responses of the narrow range SG water level at 5% and 100 % powers.
Step in feed-water flow rate (a) step in steam flow rate (b)

3. Controller Design

Output Tracking:

To minimize the effects of parameter approximation one leads to minimize the

Cost functional,

$$J_1=\int_0^\infty [x^T{}_{pq}(t)Q_1 x_{pq}(t)+u^T{}_{pq}(t)R_1 u_{pq}(t)]dt \qquad (11)$$

where Q_1 and R_1 are constant weighting matrices that must be selected by the designer. The constant state weighting matrix Q_0 is selected to be symmetric and at least positive semi-definite and the control weighting matrix R_1 is selected to be symmetric and positive definite. Under these assumptions the value of J_1 is nonnegative. The optimal control vector $u_{pq}(t)$ is generated from the state perturbation $x_{pq}(t)$ by a linear constant gain feedback:

$$u_{pq}(t)=\text{-K}\,x_{pq}(t) \qquad (12)$$

where K is a constant feedback gain matrix given by: [3].

$$\text{K}=R_1{}^{-1}B^T{}_{bq}\ P_1 \qquad (13)$$

and P_1 is a constant symmetric positive definite matrix which is the solution of the algebraic matrix Riccati equation,

$$P_1 A_{pq}+A^T{}_{pq}P_1+Q_1-P_1 B_{pq}R_1{}^{-1}B^T{}_{bq}P_1=0 \qquad (14)$$

Then we can show that:

$$U_{pq}=-Kx_{pq}(t)=-K_1 x_p-K_2 q \quad \text{where} \quad K=\begin{bmatrix}k_1 & k_2\end{bmatrix}=\text{LQR}(A_{pq}, B_{pq},\ Q_1,\ R_1) \qquad (15)$$

The existence and uniqueness of solution for the above equation are guaranteed by the following assumptions:

1. $(A_{pq},\ B_{pq})$ is a controllable pair,

2. $(A_{pq},\ Q_1^{1/2})$ is an observable pair.

Under these assumptions the closed loop system:

$$\dot{X}_{pq}(t) = (A_{pq} - B_{pq}K)x_{pq}(t) + F_{pq}(t)w(t) + H_{pq}y_r \tag{16}$$

is asymptotically stable. This implies $\dot{q} \to 0 \quad as \quad t \to \infty \quad and \quad y \to y_r$.

The complete system with tracking controller can be represented by the following block diagram.

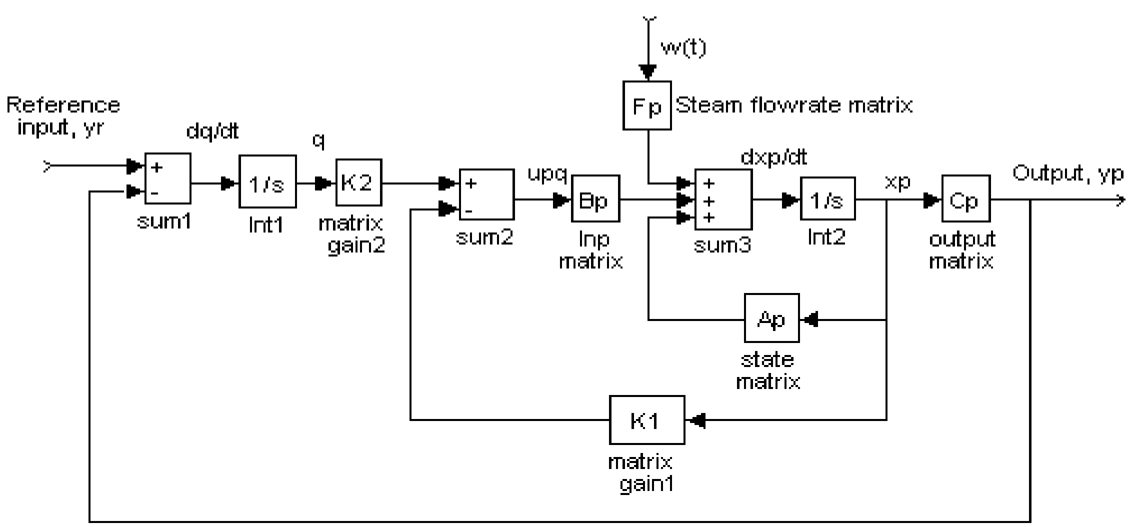


Fig. 3. Block diagram of the control system for output tracking

The dynamic parameters with respect to operating power linearized at different

Power level [16] is shown in the table below:

Table 1

$q_v(kg/s)$	57.4	180.8	381.7	660	1435
P (%power)	5	15	30	50	100
G_1	0.058	0.058	0.058	0.058	0.058
G_2	9.63	4.46	1.83	1.05	0.47
G_3	0.181	0.226	0.310	0.215	0.105
τ_1	41.9	26.3	43.4	34.8	28.6
τ_2	48.4	21.5	4.5	3.6	3.4
T	119.6	60.5	17.7	4.2	11.7

The elements of A_p matrices are graphed below to show their variations with operating power.

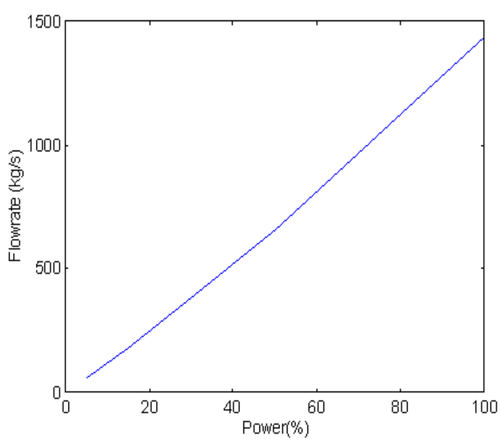


Fig. 4 Steam flowrate variation with power

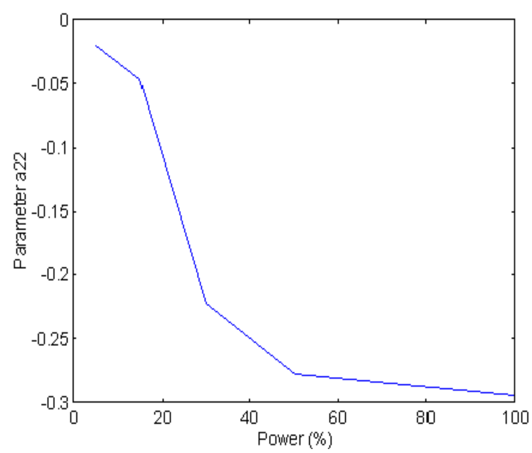
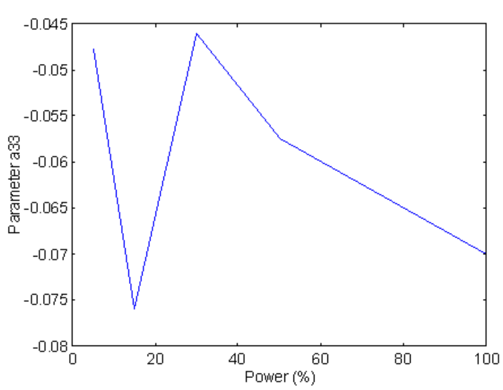


Fig. 5 Variation of element a22 with power



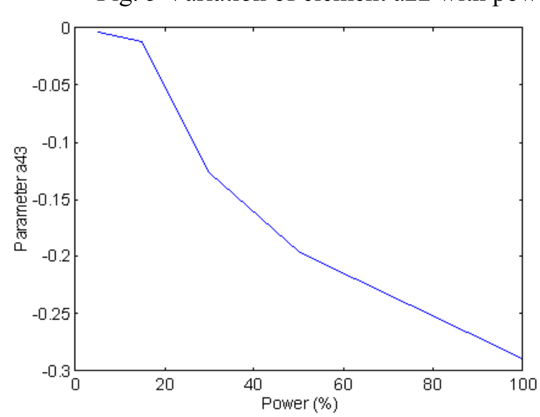


Fig. 6. Variation of element a33 with power

Fig. 7. Variation of element a43 with power

4. Simulation Results

We used a linear parameter varying model of (SG) water level of which parameters depends on the reactor power level. The model is linearized over four regions. The regions are divided according to operating power as: Region I for 0% ≤ power ≤ 15%, Region II for 15% ≤ power ≤ 30%, Region III for 30% ≤ power ≤ 50%, and Region IV for 50% ≤ power ≤ 100%. Over each region the elements of model matrices are assumed to vary linearly. We used continuous time model of the plant and applied Linear Quadratic Regulator (LQR) technique to follow a desired water level pattern. Our model is represented as a function of feed-water flow- rate. Steam flow rate and SG water level. Robust tracking is achieved for a certain range of drifts. MATLAB software package is used to generate computer simulation results. The cost matrices selected are a reasonable compromise states and the control actions.

The chosen cost matrices Q=Diag (6, 0.4, 0.04, 0.04, 0.04) and R= 10^4 [17] and the resulting constant feedback gain matrix K= [0.6572 0.1023 -0.0006 0.5870 0.0020] for Power =5% and K=[0.2484 0.0068 0.0000 0.0067 0.0020] for Power =100%. The results validate the effectiveness of the controller in SG water level.

5. Conclusion

Control of SGL strongly affects nuclear power availability. There has been a special interest in this problem during low power transients because of the dominant reverse thermal dynamic effects known as shrink and swell. In this work, a model-based Steam Generator Level Control was developed to control the water level of nuclear steam generators at 5% to 100% nominal power. Comparisons between robust model based and a PI controller show an improvement in water level set-point tracking and an increased ability in disturbance-steam flow rate changes rejection.

6. References

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Appendix 1

Observer Design:

kalman designs a given a state-space model of the plant and the process and measurement noise covariance data. The Kalman estimator is the optimal solution to the following continuous or discrete estimation problems. The implementation of the controller requires that the full state of the system is available. To estimate the states from the output measurements we use Kalman state estimator.

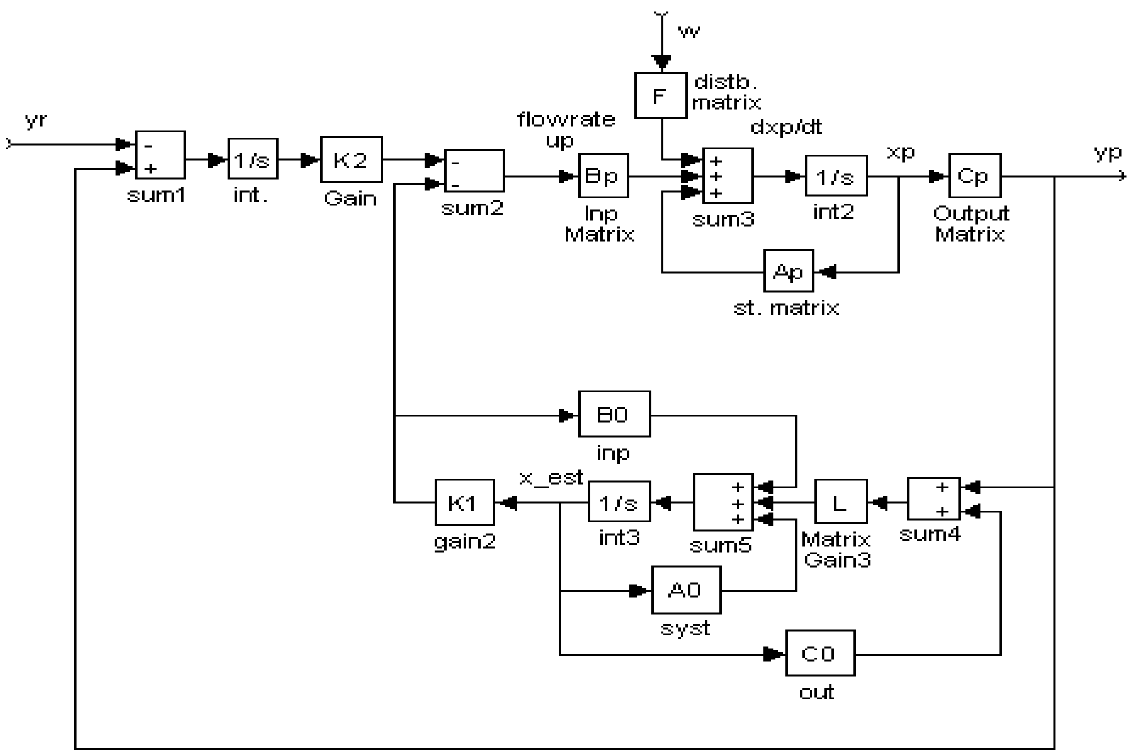
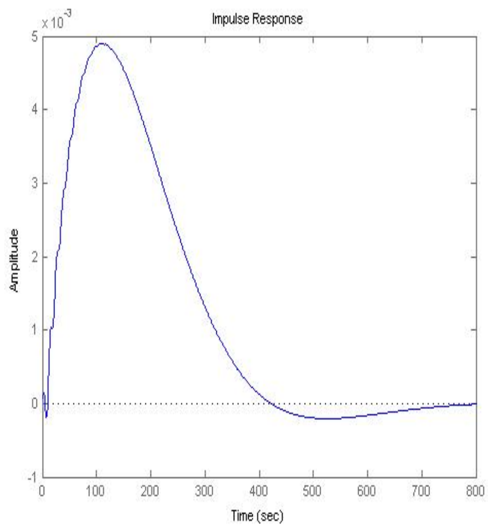


Fig. 8. Block diagram of the Kalman estimator

Appendix 2
Simulation Results:



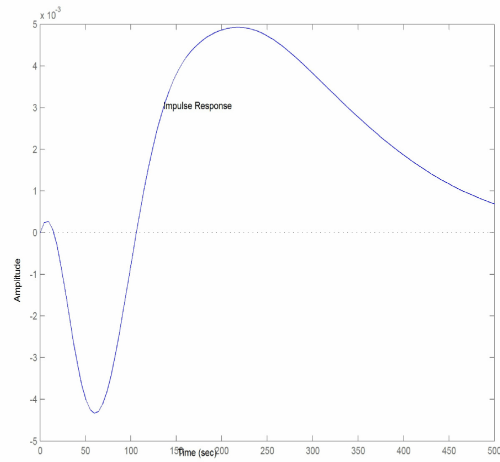
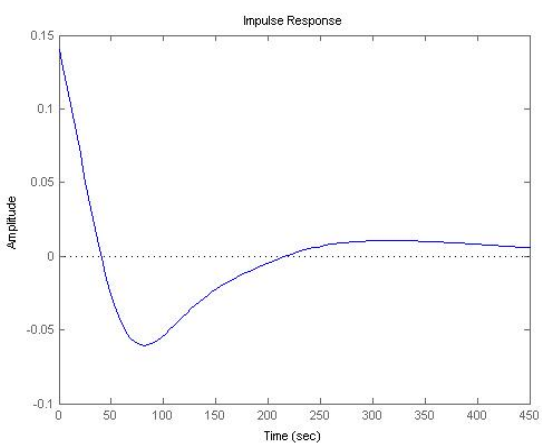


Fig. 9. SGL at 100% power for SGL Set-Point perturbation. Fig. 10. SGL Change at 5% power for SGL Set-Point perturbation.



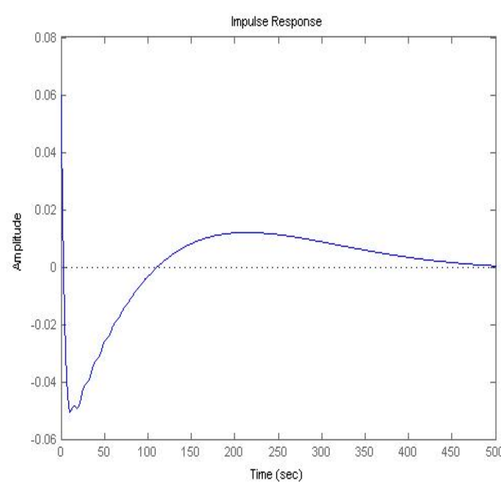


Fig. 11 SGL Change at 100% Power for Load perturbation. Fig. 12 SGL Change at 5% Power for Load perturbation.

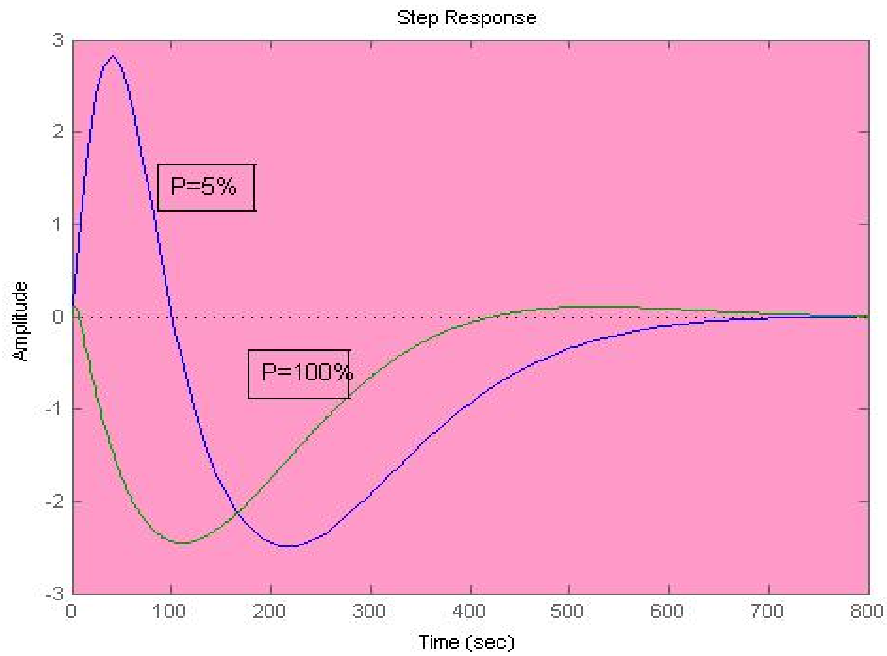


Fig. 13 SGL Change at 5% & 100% Power for Load change.

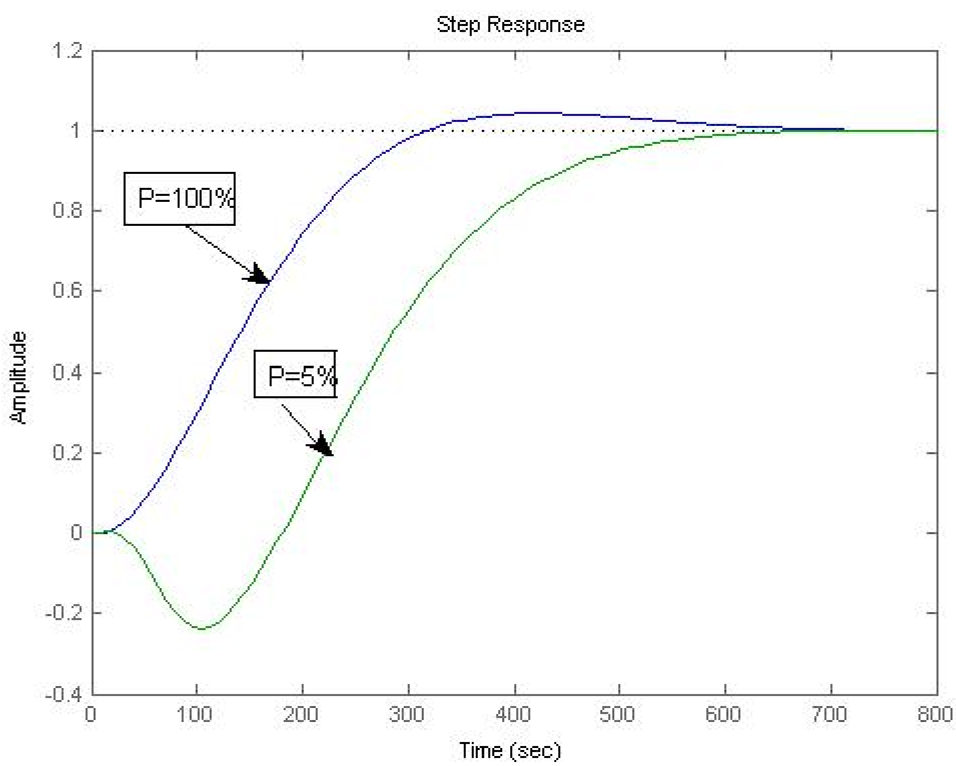
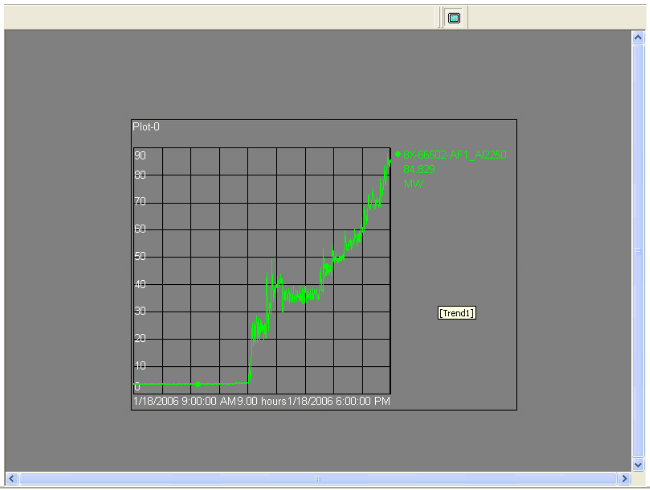
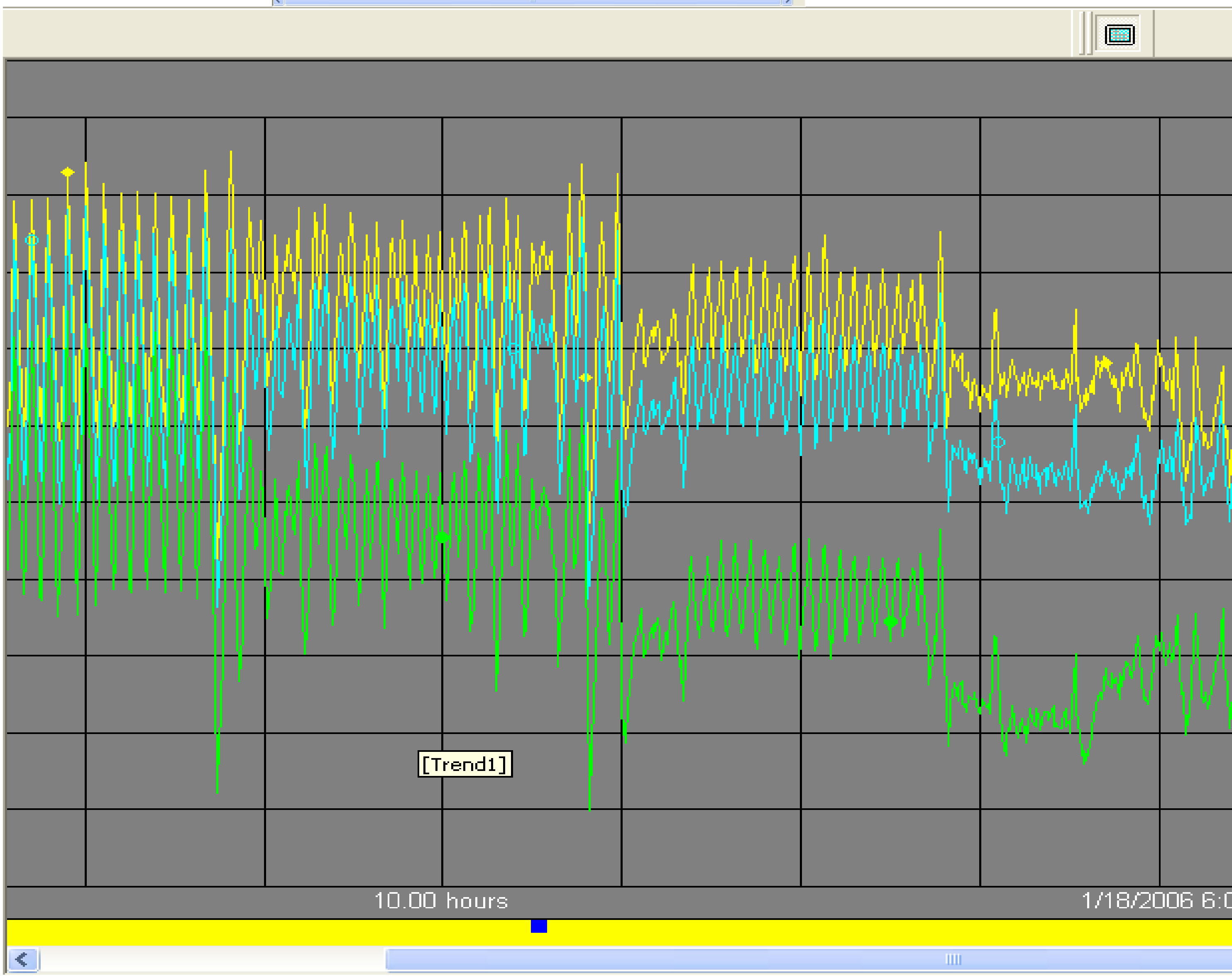


Fig. 14 SGL Change at 5% & 100% Power for Level Set-Point change.

Appendix 3

Typical (SG) Level at low power operation:





Appendix 4

SGL Response for PI controller

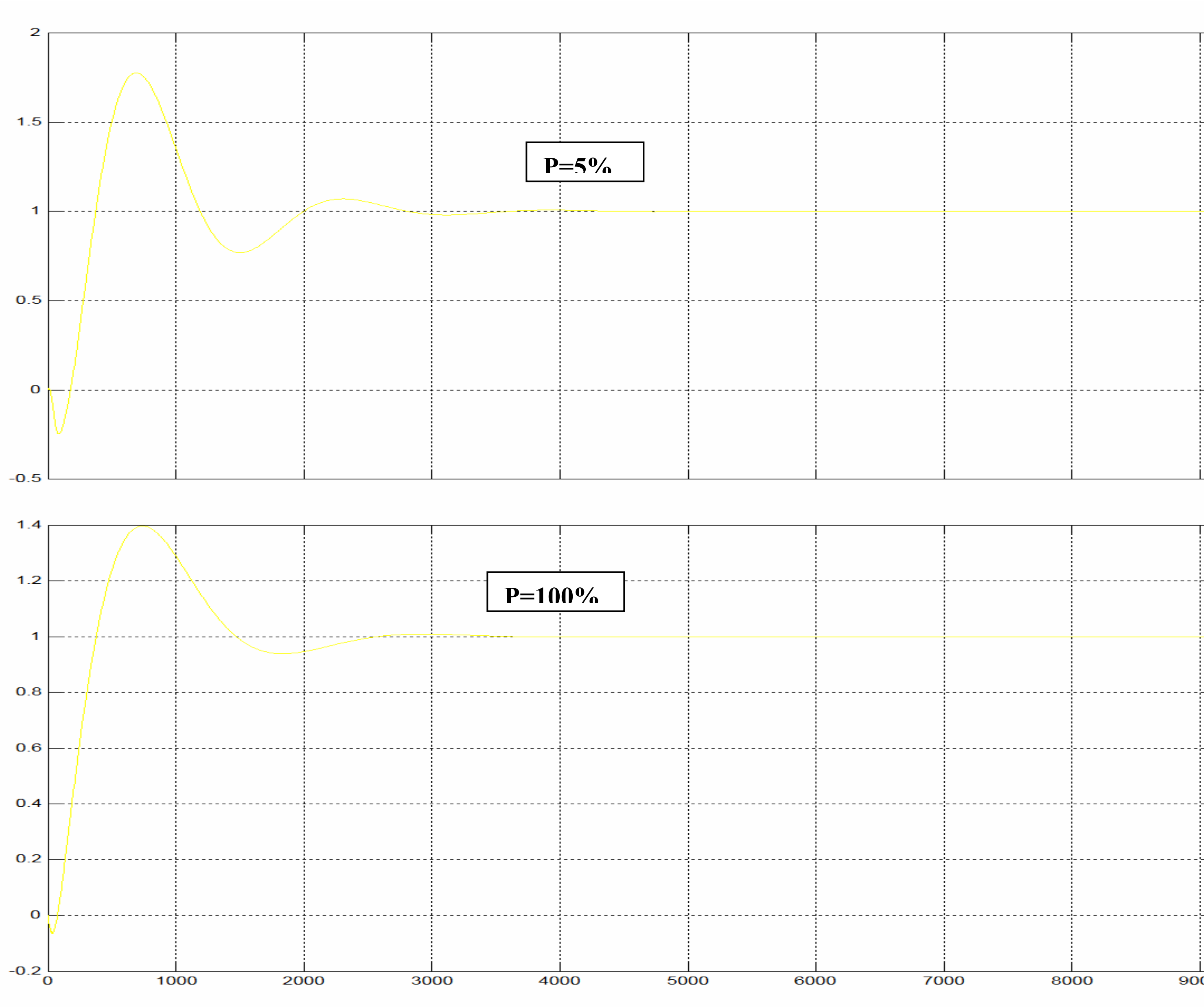


Fig. 15 SGL Step Response for PI controller