Synthesis of Model Based Robust Stabilizing Reactor Power Controller for Nuclear Power Plant

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ABSTRACT

In this paper, a nominal SISO (Single Input Single Output) model of PHWR (Pressurized Heavy Water Reactor) type nuclear power plant is developed based on normal moderator pump-up rate capturing the moderator level dynamics using system identification technique. As the plant model is not exact, therefore additive and multiplicative uncertainty modeling is required. A robust perturbed plant model is derived based on worst case model capturing slowest moderator pump-up rate dynamics and moderator control valve opening delay. Both nominal and worst case models of PHWR-type nuclear power plant have ARX (An Autoregressive Exogenous) structures and the parameters of both models are estimated using recursive LMS (Least Mean Square) optimization algorithm. Nominal and worst case discrete plant models are transformed into frequency domain for robust controller design purpose. The closed loop system is configured into two port model form and H_∞ robust controller is synthesized. The H_∞ controller is designed based on singular value loop shaping and desired magnitude of control input. The selection of desired disturbance attenuation factor and size of the largest anticipated multiplicative plant perturbation for loop shaping of H_∞ robust controller form a constrained multi-objective optimization problem. The performance and robustness of the proposed controller is tested under transient condition of a nuclear power plant in Pakistan and found satisfactory.

Key Words: **ARX Model, Uncertainty Modeling, Robust Control, H_∞ Loop Shaping, Multi-Objective Optimization, Nuclear Power Plant.**

1. INTRODUCTION

The PHWR-type nuclear power plant is one of the most popular types of nuclear power plants operating in the world. In PHWR-type nuclear power plant, the conventional reactor power controller controls the reactor power by manipulating the moderator control valve. This in turn results in the variation of moderator level in the calandria. In existing power control system, compensator based hard wired control logic is used. This compensator based control system uses number of checks and variable saturation limits on controller signals based on plant power demand conditions. Modifications in control system and design changes with time are not possible with this hard-wired controller. Therefore, it is required to design a model

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based robust stabilizing reactor power soft controller capable of addressing future process variations in terms of moderator level dynamics and process delays. The details of this conventional reactor power control system are discussed in [1]. In model based controller design, the most important thing is to develop a mathematical model of a nuclear power plant which is to be controlled. There are models for nuclear reactors in nuclear reactor codes but their complex nature does not allow model-based controller design [2]. In [2-5], various modeling issues are addressed for different research and power reactors. Pole placement and LQR (Linear Quadratic Regulator) type robust optimal controllers have been identified in [6] for research reactors and PWR (Pressurized Water Reactor) type nuclear power reactors. A robust optimal LQR controller has been designed for reactor power control using stochastic search method in [7]. In [8], a robust feedforward/feedback controller has been proposed for BWR (Boiling Water Reactor) type nuclear power plant. A robust reactor power controller has been designed for research reactor using micro-synthesis technique in [9]. A system identification based model of a PWR type nuclear power plant has been developed in [10] and based on this model a robust controller using extended frequency response method has been addressed. A robust controller has been proposed for research reactor power controller using coprime factorization approach in [11]. In [12], a H_∞ controller has been proposed for linear missile system using lead-lag type loop shaping weighting functions. A robust H_∞ control design problem has been investigated for aircraft system with parameter variations and disturbance uncertainties in [13]. In [14], a weighting function has been determined for output sensitivity function in an H_∞ optimization approach which assures partial pole placement and desired performance. A nodal model of PHWR-type nuclear reactor has been developed based on first principles and different controllers have been proposed in [15-17] but uses LZC (Liquid Zone Control) for reactor power control. An attempt has been made for robust H_∞ controller design for a PHWR-type nuclear reactor using normalized coprime factorization approach in [18].

The problem of robust control system capable of noise reduction and disturbance rejection for PHWR-type nuclear power plants is not much investigated in literature. The H_∞ controller design technique provides an efficient tool which can deal with the modeling errors and external disturbances. In contact with control design work proposed in [1] and [15-17] which stresses the performance of linear and nonlinear controllers only, the H_∞ control optimizes both the performance and robustness resulting in meaningful optimizations. In [1], an attempt has been made to design a model based discrete two-time scale controller for a different PHWR [19] uses MLC (Moderator Level Control) but the issues of modeling uncertainty, process delays and controller robustness have not been addressed. In this research work, these issues are resolved by considering modeling uncertainty and synthesizing a robust controller that guarantees both robustness and performance. Therefore, this research work is different from [12-14 and 18] and one step ahead after incorporating worst case moderator level dynamics, process delays, plant uncertainty modeling, MLC (Moderator Level Control) system for a different PHWR [19] and H_∞ multi-objective optimization for robust stabilizing controller design based on two-port modeling approach, LFT (Linear Fractional Transformation), singular value loop shaping design approach, desired magnitude of control input and an optimization in the framework of Riccati equations.

2. SYSTEM IDENTIFICATION TECHNIQUE

In a system identification method, a black box modeling approach is adopted. The type of model structure and the parameter are derived from the measured data of input and output of a plant. The details of PHWR-type NPP processes are discussed in [1]. The ARX model is the simplest empirical parametric model incorporating the stimulus signal. The estimation of the ARX model is the most efficient of the polynomial estimation methods because it is the result of solving linear regression equations in analytic form. Moreover, the solution satisfies the global minimum of the loss function for a linear SISO system.

3. IDENTIFICATION OF PHWR NPP MODEL

A system identification application consists of an unknown system that has an input signal, or stimulus signal u(k) and an output signal, or response signal y(k). The moderator valve position is used as stimulus or an input signal while reactor power is used as an output signal for system identification purpose.

3.1 Nominal PHWR NPP Model

The nominal plant model is identified at a normal moderator pump up rate of 0.254 cm/sec [19]. Based on ARX modeling procedure [20], the discrete nominal SISO model of the PHWR-type nuclear power plant has been identified at a sample time (T_s) of 0.16 second as [1]:

$$G_N(z) = \frac{y_N(z)}{u_N(z)} = \frac{0.648 - 1.1311z^{-1} + 0.6107z^{-2} - 0.0929z^{-3} - 0.000391z^{-4}}{1 - 2.085z^{-1} + 1.4754z^{-2} - 0.4087z^{-3} + 0.04306z^{-4} - 0.00109z^{-5}} \quad (1)$$

The discrete time SISO transfer function model of Equation (1) can be converted into continuous time SISO transfer function model using Tustin approximation method which is as follows:

$$z = \frac{1 + sT_S/2}{1 - sT_S/2} \quad (2)$$

Tustin approximation method is selected for robust controller design because it is desired to have a good frequency domain matching between discrete system time model and corresponding continuous-time model.

Therefore, the continuous time SISO transfer function model of Equation (1) can be obtained using Tustin approximation mehtod as:

$$G_N(s) = \frac{y_N(s)}{u_N(s)} = \frac{0.648s^4 - 0.61788s^3 + 0.08698s^2 - 0.001397s - 0.000701}{s^5 - 1.209s^4 + 0.45773s^3 - 0.05622s^2 + 0.001478s - 0.000026} \quad (3)$$

3.2 Worst PHWR NPP Model

The worst case plant model is identified using innovative data at a slowest moderator pump up rate of 0.0254 cm/sec [19]. Based on ARX modeling procedure [20], the discrete worst SISO model of the PHWR-type nuclear power plant is identified at a sample time of 0.16 second. The continuous worst plant model is obtained as:

$$G_W(s) = \frac{y_W(s)}{u_W(s)} = \frac{0.873s^4 - 0.924s^3 + 1.677s^2 - 0.0283s - 0.0043}{s^5 - 84.311s^4 + 66.4383s^3 - 3.549s^2 + 0.076s - 0.011} \quad (4)$$

3.3 Delay Modeling

The control valve delay has a great effect on the system performance and stability. The maximum time delay (T_d) in control valve opening is two seconds as reported in [19]. A second order Pade approximation is implemented for delay modeling of 2 seconds:

$$D(s) = e^{-T_d s} = e^{-2s} = \frac{s^2 - 3s + 3}{s^2 + 3s + 3} \quad (5)$$

3.4 Perturbed PHWR NPP Modeling

The perturbed plant model is given as follows:

$$G_p(s) = G_W(s)\, D(s) \quad (6)$$

4. UNCERTAINTY MODELING

Since plant model is not exact, so the model has uncertainties. Normally the plant models are nonlinear in nature. But the identified nominal plant model is a linear higher order. Therefore, the uncertainties arise from nonlinearities of actual plant model, assumptions in identification procedure, actuator delay (i.e. moderator control valve) and improper moderator pump up rate due to aging of plant process components in PHWR-type nuclear power plant.

4.1 Unstructured Uncertainty

The unstructured uncertainty represent frequency dependent elements such moderator control valve saturations and unmodeled aging effects of process components. Their relations to the nominal plant can be either additive or multiplicative. Both can be considered as norm bounded quantities.

4.2 Additive Unstructured Uncertainty

The additive unstructured uncertainty is computed as follows:

$$\Delta_A(s) = G_P(s) - G_N(s) \tag{7}$$

4.3 Multiplicative Unstructured Uncertainty

The multiplicative unstructured uncertainty is computed as follows:

$$\Delta_M(s) = \frac{G_P(s) - G_N(s)}{G_N(s)} \tag{8}$$

5. PLANT DISTURBANCE AND SENSOR NOISE

Since nuclear power plant is a complex system and therefore there will be a great influence of plant disturbance and sensor noise on the reactor power control system. The block diagram of reactor power control with disturbance and noise effect is shown in Fig. 1. Normally, the disturbance has low frequencies effect and noise has high frequencies effect on the control system.

5.1 Two Port Model of PHWR Power Control System

The continuous nominal plant model described in Equation (3) can be expressed in standard state space form as:

$$\dot{x}(t)(t) = Ax(t) + Bu(t) \tag{9}$$

$$y_N(t) = C\,x(t)$$

where $A \in R^n$ is 5x5 system matrix, is 5x1 input matrix and is 1x5 output matrix.

The closed loop reactor power control system shown in Fig. 1 is drawn into two port model form consists of augmented plant $G_A(s)$ and controller K(s) as shown in Fig. 2.

$B \in R^n$

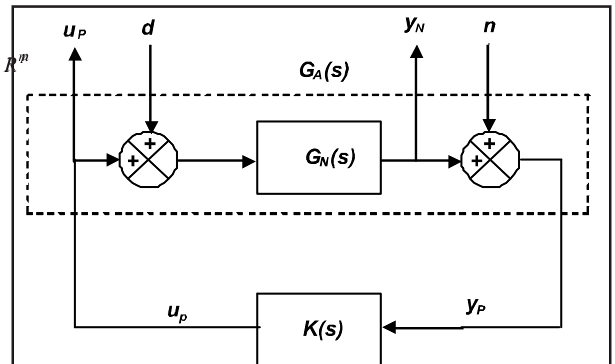

FIG. 2. TWO PORT MODEL OF PHWR POWER CONTROL SYSTEM

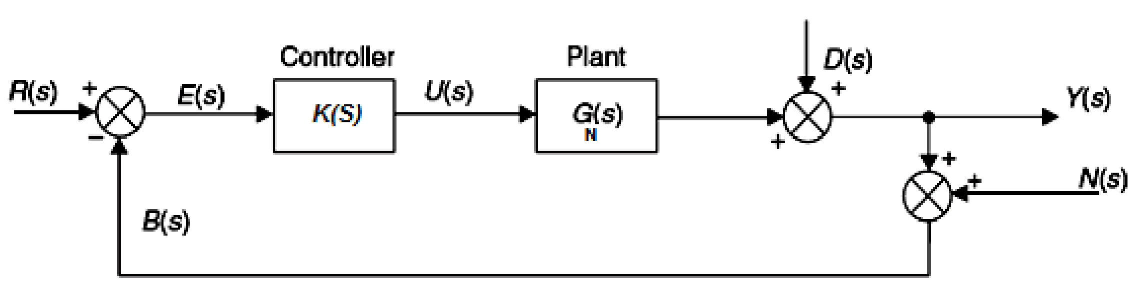

FIG. 1. NUCLEAR REACTOR POWER CONTROL SYSYEM WITH DISTURBANCE AND NOISE

If w is the exogenous input vector containing exogenous signals such as disturbance d and noise n and z the exogenous output vector containing exogenous signals such as nominal plant output yN and control signal u while y_P is the perturbed plant output.

Then the two port model of the perturbed plant shown in Fig. 2 can be expressed in two port state space from as:

$$\begin{aligned} \dot{x}(t) &= Ax(t) + B_1 w(t) + B_2 u(t) \\ z(t) &= C_1 x(t) + D_{11} w(t) + D_{12} u(t) \\ y_P(t) &= C_2 x(t) + D_{21} w(t) + D_{22} u(t) \end{aligned} \tag{10}$$

where A is the same system matrix and B_2=B while the other matrices and vectors can be defined as:

$$B_1 = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T, C_1 = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$C_2 = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \end{bmatrix}, D_{11} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}, D_{12} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

$$D_{21} = \begin{bmatrix} 0 & -1 \end{bmatrix}, D_{22} = 0$$

The augmented plant matrix $G_A(s)$ can be written as:

$$G_A(s) = \begin{bmatrix} A & B_1 & B_2 \\ C_1 & D_{11} & D_{12} \\ C_2 & D_{21} & D_{22} \end{bmatrix} = \begin{bmatrix} G_{A11} & G_{A12} \\ G_{A21} & G_{A22} \end{bmatrix} \tag{11}$$

6. SENSITIVITY ANALYSIS

In order to quantify the robust stability margin and robust system performance, output sensitivity function S(s) and input complementary sensitivity function T(s) are computed.

6.1 Output Sensitivity Function

The output sensitivity function is given by:

$$S(s) = \frac{1}{1 + G_N(s)K(s)} \tag{12}$$

6.2 Input Complementary Sensitivity Function

The input complementary sensitivity function is given by:

$$T(s) = \frac{G_N(s)K(s)}{1 + G_N(s)K(s)} \tag{13}$$

where

$$S(s) + T(s) = I \tag{14}$$

where I is an identity matrix.

6.3 Nyquist Small Gain Theorem

According to Nyquist small gain theorem, the system is robust subject to the following conditions:

$$(1)\left|\Delta_A(s)\right| < \frac{1}{\left|K(s)(1 + G_N(s)K(s))^{-1}\right|} = \frac{1}{\left|K(s)S(s)\right|} \tag{15}$$

$$(2)\left|\Delta_M(s)\right| < \frac{1}{\left|G_N(s)K(s)(1 + G_N(s)K(s))^{-1}\right|} = \frac{1}{\left|T(s)\right|} \tag{16}$$

It is required to minimize the S(s) in low frequency region and T(s) in high frequency region in order to eliminate the effect of disturbance and noise respectively.

6.4 Singular Value Loop Shaping

Now the values of S(s) and T(s) are so computed that Equations (15) and (16) are satisfied for robustness due to additive and multiplicative uncertainties.

The singular value of sensitivity function $\overline{\sigma}(S(j\omega))$ determine the disturbance attenuation, and therefore the performance specification is described as:

$$\overline{\sigma}(S(j\omega)) \le \left|W_S^{-1}(j\omega)\right| \tag{17}$$

If $\Delta_M(s)$ is a diagonal matrix of multiplicative plant uncertainty then the size of the smallest stable $\Delta_M(s)$ for which the system becomes unstable is:

$$\bar{\sigma}(\Delta_M(j\omega)) = \frac{1}{\bar{\sigma}(T(j\omega))} \tag{18}$$

or alternatively it can be written as:

$$\bar{\sigma}(T(j\omega)) \le \left|W_T^{-1}(j\omega)\right| \tag{19}$$

where $\left|W_T^{-1}(j\omega)\right|$ is the size of the largest anticipated multiplicative plant uncertainty.

The singular value Bode magnitude plot for plant nominal model is shown in Fig. 3 while the singular value Bode magnitude plots for weighting functions are shown in Fig. 4. The response shown in Fig. 4 is basically the frequency response of the reciprocal of the weighting functions.

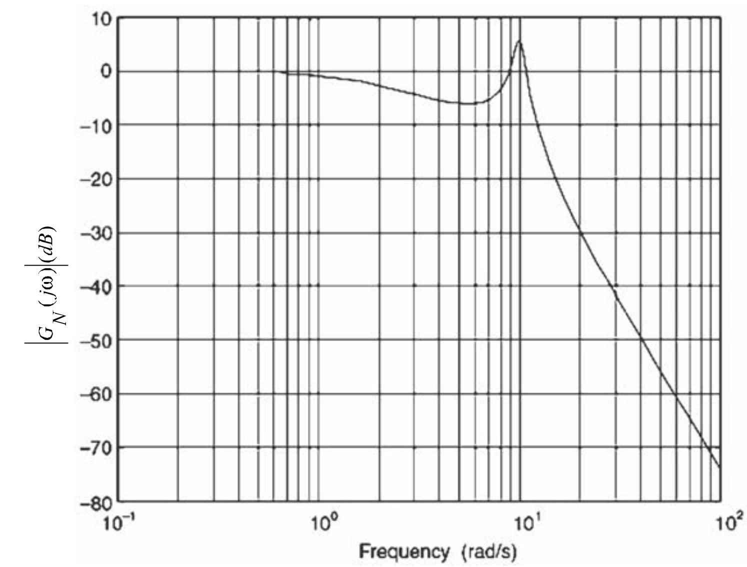

FIG. 3. SINGULAR VALUE BODE MAGNITUDE PLOT OF NOMINAL PLANT MODEL

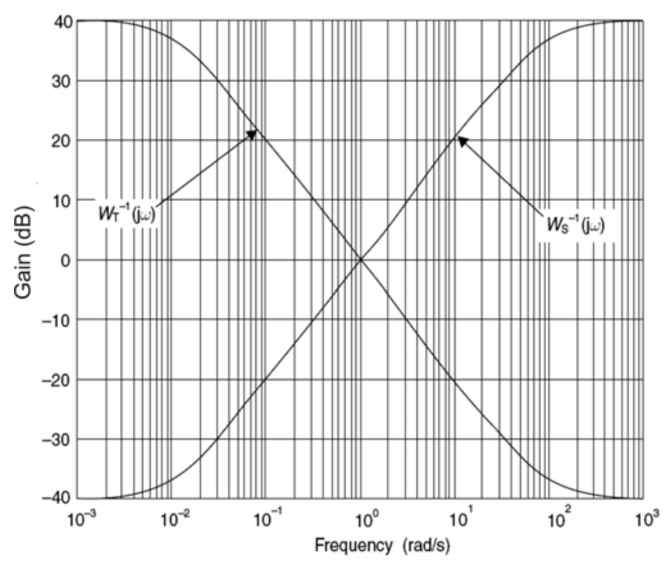

FIG. 4. SINGULAR VALUE BODE MAGNITUDE PLOTS OF WEIGHTING FUNCTIONS

7. H_∞ CONTROLLER SYNTHESIS

H_∞ is a very reliable technique for robust controller design. Robust stability provides a minimum requirement in an environment where there is a plant model uncertainty. For a control system to have robust performance it should be capable of minimizing the error for worst plant model.

Using LFT (Linear Fractional Transformation), the H_∞ control problem is to find a controller K(s) that minimizes the overall norm of the closed loop system:

$$\left\| T_{ZW} \right\|_\infty = \max_{\omega} \bar{\sigma}(F_l(G_A, K)(j\omega)) < \gamma \tag{20}$$

where $\bar{\sigma}(.)$ is the singular value of lower linear fractional transformation transfer function and is the H_∞ norm.

The lower linear fractional transformation transfer function is given as [21]:

$$T_{ZW}=F_l(G_A,K)=G_{A11}(s)+G_{A12}(s)K(s)[I-G_{A22}(S)K(S)]^{-1}G_{A21}(s) \tag{21}$$

$$\begin{bmatrix} z(t) \\ y_P(t) \end{bmatrix} = \begin{bmatrix} G_{A11} & G_{A12} \\ G_{A21} & G_{A22} \end{bmatrix} \tag{22}$$

The following design constraint is imposed on the output signal:

$$y_{P_{\min}}(t) \le y_P(t) \le y_{P_{\max}}(t) \tag{23}$$

The robust control law can be described as:

$$u_P(t) = K(s)\, y_P(t) \tag{24}$$

The following design constraint is imposed on the control input signal:

$$u_{P_{\min}}(t) \le u_P(t) \le u_{P_{\max}}(t) \tag{25}$$

The condition for the existence of H_∞ controller is that there should exist a positive semi-definite stabilizing solution P_∞ satisfying the following ARE:

$$P_\infty \tilde{A} + \tilde{A}^T P_\infty - (B_2 B_2^T - \gamma^{-1} B_1 B_1^T) P_\infty + \tilde{C}^T \tilde{C} = 0 \tag{26}$$

where

$$\tilde{A} = A - B_2 D_{12}^T C_1, \tilde{C}^T \tilde{C} = C_1^T (I - D_{12} D_{12}^T) C_1$$

The state space form of H_∞ controller is given as:

$$K(s) = \begin{bmatrix} \tilde{A} - P_\infty B_2 B_2^T & P_\infty P_2^T \\ B_1 & 0 \end{bmatrix} \tag{27}$$

The stability margin b(G(s),K(s)) is given as follows [18]:

$$b(G_N(s), K(s)) = \left\| \begin{bmatrix} I \\ K(s) \end{bmatrix} \left[I - G_N(s) K(s) \right]^{-1} \left[G_N(s) I \right] \right\|_\infty^{-1} \tag{28}$$

The prescribed H_∞ performance is computed as follows:

$$\gamma = \frac{1}{b(G_N(s), K(s))} \tag{29}$$

The singular value Bode magnitude plot of cost function is shown in Fig. 5. This singular value bode plot shows the infinity norm variation of closed loop cost function in terms of sensitivity weighting function. The singular value Bode magnitude plot of controller is shown in Fig. 6. The variation of singular value bode plot shows the aggressive robust behavior of controller against model uncertainty, noise and disturbance. The singular value bode plot of the controller shows large robustness with increased gain and phase margins for enhanced system performance.

7.1 Multi-Objective Optimization Problem

The stability of the closed loop robust control problem is guaranteed by satisfying the following six objectives:

(1) To keep all the closed loop eigenvalues in left half of s-plane (i.e. all λ_i<-1; i=1,2,…,5).

(2) To ensure a critically damped closed loop control system (i.e. no overshoot system).

(3) To minimize the H_∞ norm (i.e. maximize the robustness of closed loop control system).

(4) To minimize the ITAE of the step response of the closed loop control system (i.e. quickest settling rime).

(5) To keep the control signal within design constraints (i.e. 32% < $u_p(t)$ < 100%).

(6) To keep the output signal within design constraints (i.e. 0 < $y_p(t)$ < 112%).

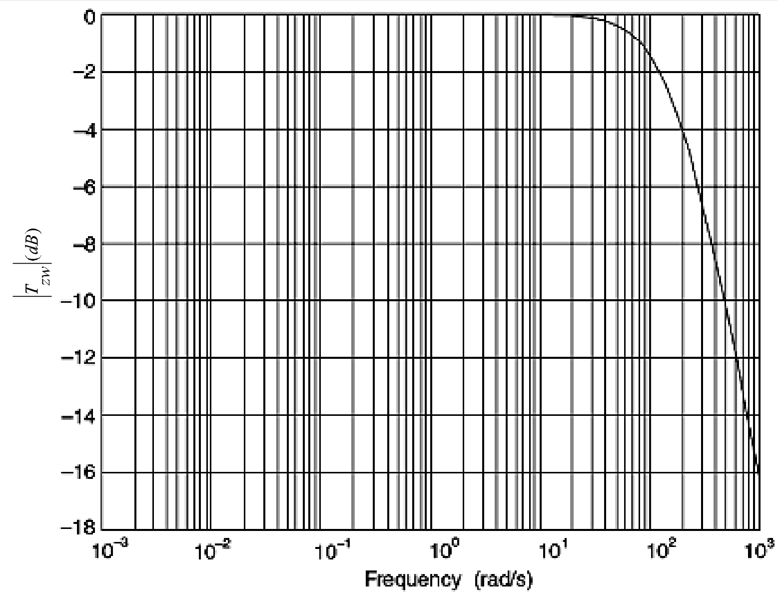

FIG. 5. SINGULAR VALUE BODE MAGNITUDE PLOT OF COST FUNCTION

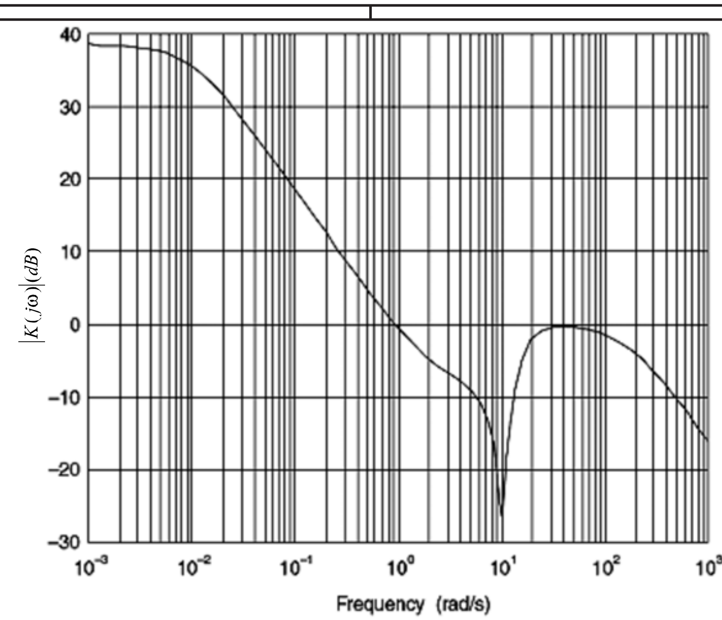

FIG. 6. SINGULAR VALUE BODE MAGNITUDE PLOT OF CONTROLLER

8. ROBUSTNESS AND PERFORMANCE ANALYSIS

The design of H_∞ controller depends on the way by which the exogenous signals act on the two port model of closed loop control system. Therefore, the H_∞ controller is synthesized by changing the state variable on which the disturbance acts from x_1 to x_5. It has been proved in [1] that the nominal plant model has three slow states (i.e. x_1, x_2 and x_3) and two fast states (i.e. x_1 and x_2) based on eigenvalue analysis. The magnitude of controller has a drastic effect on controller response and system speed. When the magnitude of controller is small then the gain and phase margins are large. These large gain and phase margins are very useful for system robustness but undesirable for system performance. Various simulation experiments are performed and the effects of disturbance interaction with states are observed. It is observed that the system speed is very slow for slowest state (i.e. x_1) and the control effort is very small. Hence the system has poor performance with excessive robustness. Whereas the system speed is very fast for fastest state (i.e. x_5) and the control effort is large. Hence the system has good performance with poor robustness. Thus, performance and robustness has to be traded off. Therefore, an optimal situation is obtained by decreasing the magnitude of H_∞ controller. In H_∞ controller design, another design consideration is the magnitude of control input. The magnitude of control input means moderator control valve position. The maximum moderator control valve opening is about 1%/sec [15]. After implementing the constraint on the control input signal, the H_∞ controller is designed using Robust Control tool of MATLAB.

The transfer function of the designed H_∞ controller at its optimal value (λ=0.017) is given as:

$$K(s) = \frac{152s^4 + 12.75\times10^3 s^3 + 55.13\times10^3 s^2 + 1.39\times10^6 s + 2.98\times10^6}{s^5 + 266s^4 + 18.25\times10^3 s^3 + 298.51\times10^3 s^2 + 2.14\times10^6 s + 44.56\times10^3} \qquad (30)$$

The performance of closed loop system is investigated when the reactor is initially at 80% power level and the demand is changed to 90%. This power maneuvering of 10% is achieved by a step function. Control signal changes from 32 to 33% in 1.5 second and then quickly stabilizes in about 20 seconds. The plant output changes from 80-90% without any overshoot and the new steady state power is achieved in 20 seconds. Therefore, the setting time for this power transient is 20 seconds. The closed loop step response of robust reactor power control system is shown in Figs. 7-8. In Fig. 7, the dynamics of moderator valve position is shown. The variation in moderator valve position in turn results in the rise moderator level in the calandria. The rise in moderator level results in the rise of reactor power. The predicted dynamics of moderator valve position is basically the variation of robust control law. The variation of control law is so designed to achieve a critically damped system. In critically damped system no overshoot is allowed with fast settling time. A critically damped system is the core requirement of nuclear power plant because the nuclear reactor neutronics is very much sensitive to overshoots and undershoots which may result in large variation in plant parameters and thereby may result in uncontrolled oscillations in the reactor core. Thus, the desired dynamics of the reactor power control system of PHWR-type nuclear power plant is achieved using robust control technology which proves the critically damped characteristic of proposed control system.

9. CONCLUSIONS

A nominal higher order plant model of PHWR-type nuclear power plant has been developed based on moderator level dynamics of nuclear reactor. A perturbed plant model has been derived based on slowest moderator pump up rate and moderator control valve opening delay. Thus, additive and multiplicative modeling uncertainties have been identified for robust H_∞ controller design. The singular value plot shows the desirable loop shape. Hence the designed controller is robust and capable enough for disturbance rejection at low frequencies and noise rejection at high frequencies. The performance of the model based robust stabilizing reactor power controller has been tested under transient condition and found excellent and fast.

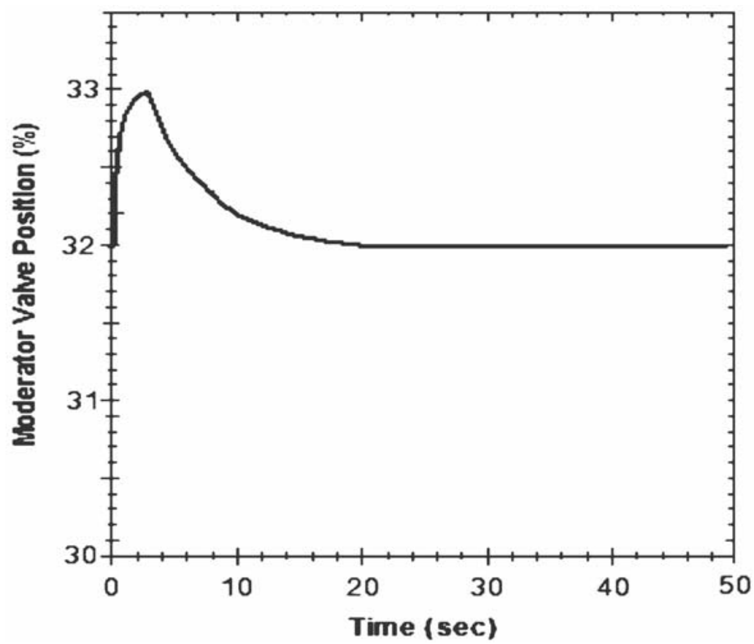

FIG. 7. CLOSED LOOP STEP RESPONSE OF MODERATOR VALVE POSITION

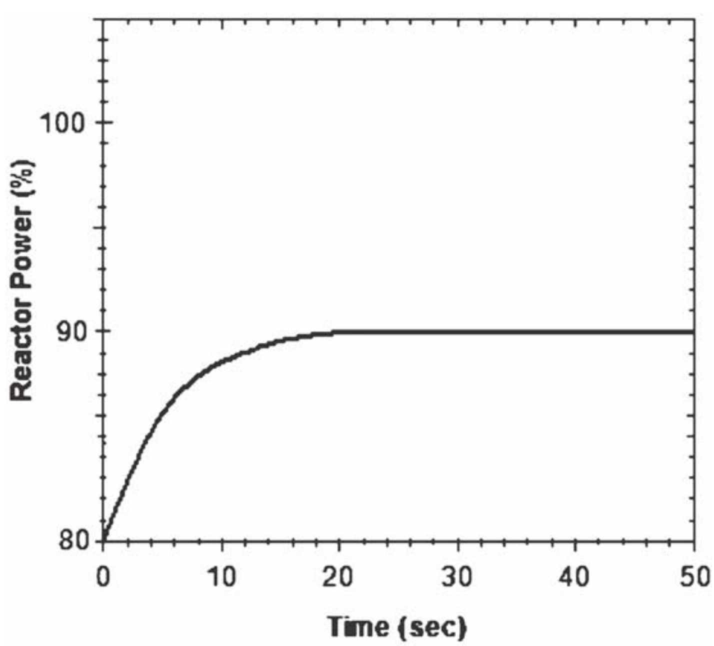

FIG. 8. CLOSED LOOP STEP RESPONSE OF REACTOR POWER

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