Robust Control of a Steam Turbine Power Based on a Precise Nonlinear Model

S.A. Salamati
Senior Researcher
Electrical Department
Niroo Research Institute
Tehran,Iran
Email: asalamati@nri.ac.ir

H.D. Taghirad
Professor
Control and Systems Department
K.N. Toosi University of technology
Tehran,Iran
Email: Taghirad@kntu.ac.ir

Ali Chaibakhsh
Associate Professor
Mechanical Department
Guilan University
Rasht,Iran
Email: chaibakhsh@guilan.ac.ir

Abstract— In this paper, a precise and nonlinear model is developed for Nekka power plant turbine from its experimental data and documents. It is proposed to use boiler-turbine coordinated control system to increase effective efficiency of the steam unit. Identification procedures have been performed to obtain continuous time models of Nekka steam turbine at various loads. After determining the upper bound for uncertainty and choosing a good performance weighting function, a robust controller has been designed and implemented in closed loop for the turbine nonlinear model. Since the closed loop performance was not as required, a cascade controller structure is proposed, in which the turbine loop is closed by a PI controller in order to significantly reduce the uncertainty. Simulation results demonstrate the suitable performance of the closed loop in terms of tracking, speed of response, and damping of oscillations.

Keywords-component; steam turbine, governor, turbine control, robust control

I. INTRODUCTION

Nowadays, the steam turbines are widely used for power generating because of their good efficiency. Too many controller procedures have been developed for different power plant applications. Through these different methods, classic controllers are more implemented in power plants because of their simplicity and low costs. According to demand increasing and complicated structure of recent power systems, modern control techniques become more applicable. Too many theories and procedures have been developed to apply modern control in power plants in last years. As examples of such controllers, many researches have been performed on LQR control, robust control, and model predictive control since 1970 to 2010[1].

Robust controller design which is generally based on H_∞ optimal problem and μ synthesis has been implemented in power systems since 1980[2-3]. Robust control modules are developed by well-known companies such as ABB, Siemens and General Electric for power plant applications. However this approach has been used for gas and combined cycle power plants and a less work has been reported on steam power plants especially steam turbines[4-5].

Steam turbines have generally a complex feature and consist of multi stage steam expansion to improve the thermal efficiency. A precise nonlinear model of the steam turbines is necessary to study their dynamics. Therefore, many models are developed for dynamics of steam turbine [6-7]. In many cases, the turbine models are such simplified that they only map input to output, and many intermediate variables are neglected [8]. The lack of accuracy in simple models controller design harder.

In this paper, the proposed model for steam turbine by Chibakhsh et al. (2008) has been used [9]. In this model, mathematical models are first developed for analysis of transient response of the steam turbine subsections based on the energy balance, thermodynamic state conversion and semi-empirical equations. Then the related parameters are either determined by empirical relations obtained from experimental data or they are adjusted by applying genetic-algorithms. In the intermediate and low– pressure turbines, in which, in sub cooled regions steam variables deviate from perfect gas behaviour, the thermodynamic characteristics are highly dependent on pressure and temperature of each region. Thus nonlinear functions are developed to evaluate specific enthalpy and specific entropy at these stages of turbine. The parameters of proposed functions are individually adjusted for the operational range of each subsection by using genetic algorithms [9].

The paper is organized as follows. In the next section, a brief description of steam turbine of Nekka power plant is given and this follows by Nekka steam turbine model. In the next section, Identification procedures are performed to obtain continuous time models of steam turbine at various loads. After determining the upper bound for uncertainty and choosing a good performance weighting function, a robust controller is designed and implemented on the turbine nonlinear model. Then, a cascade controller structure, in which the turbine loop is closed by a PI controller, is proposed in order to reduce the uncertainty. By using this structure, a

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robust controller is designed for the systems. Then simulation results are presented by comparing the responses of the proposed controller with classic PI controller. It is necessary to consider that the two controllers are implemented to the turbine in load demand coordinated control mode. The concluding remarks are given in the last section.

II. SYSTEM DESCRIPTION

A steam turbine of a 440 Mw power plant is considered for the control approach. The steam turbine comprises high, intermediate and low-pressure sections. In addition, the system includes steam extractions, feed water heaters, moisture separators, and the related actuators. The turbine configuration and steam conditions at extractions are shown in Fig. 1. [9].

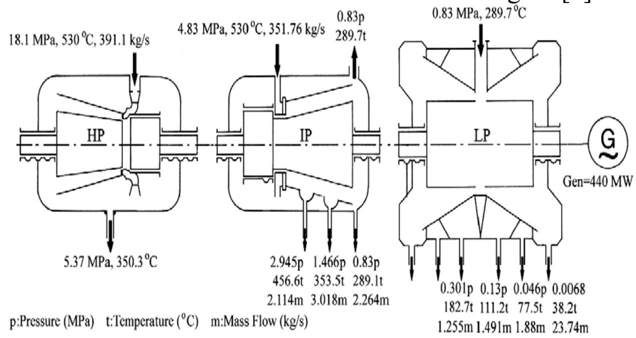

Figure 1. Steam conditions at extractions of Nekka power plant

High-pressure (HP) turbine is supplied by the super-heated steam at 535°C and 18.6 (Mpa) pressure. Turbine chest system makes the input steam pressure to drop about 0.5 (Mpa) by passing through it. The steam expands in the HP turbine and then goes into the repeater line to restore its initial temperature. At the full load, the steam output temperature in the HP turbine input is 351°c and related pressure is 5.37Mpa. This steam passes through moisture separator to lose its' humidity and after this stage The steam goes through re-heater section which is in the boiler furnace. The reheated steam at 535°C and with 4.83 (M pa) pressures is fed to Intermediate pressure (IP) turbine. Output steam from IP turbine is fed into the low-pressure (LP) turbine. The input temperature and pressure of the low-pressure turbine is 289.7°c and 0.83 (Mp), respectively. The steam from the first and second extractions is sent to HP heater and de-aerator. Extracted steam from last IP and LP extractions are used to heat the feedwater. The very low-pressure steam from the last extraction goes to condenser to become cool and be used in steam generation loop again.

III. ROBUST CONTROLLER DESIGN

The model that has been used for the design of the controller is illustrated in Fig 2. All its mathematical and numerical equations and complete models are detailed in (Chaibakhsh et al. (2008) [9]. The recent demand control structure in Nekka power plant is turbine follow. The turbine follow scheme provides a tight control on throttle pressure, but its response to load changes is very slow because the control valves do not move until firing rate has been adjusted to the new demand level. In this paper, we proposed the coordinated control structure for the plant and controller design has been performed by considering this fact. The basic principles of the coordinated control structure are that load demand is provided as a feed forward signal to both the boiler and the turbine control system in parallel while minimizing the interaction between the boiler and the turbine variables [10].

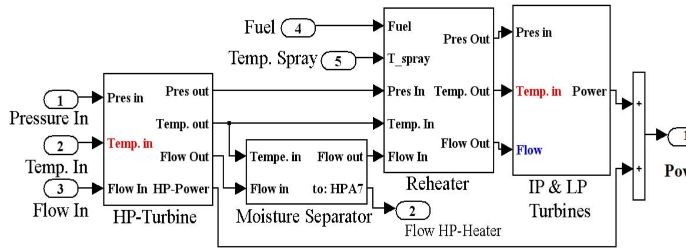

Figure 2. Block diagram of Nekka power plant

To consider the system dynamics accurately, it is necessary to consider nonlinearity of the system. However, for the purpose of control, a linear model for the system will be used. For the synthesis, an empirical method to find this nominal model is to perform a series of experimental frequency response on the system, with different input amplitudes, and to find the best fit through them. Using chirp function with different amplitudes, a set of frequency response estimates for the system is generated. The frequency responses are illustrated in Fig. 3.

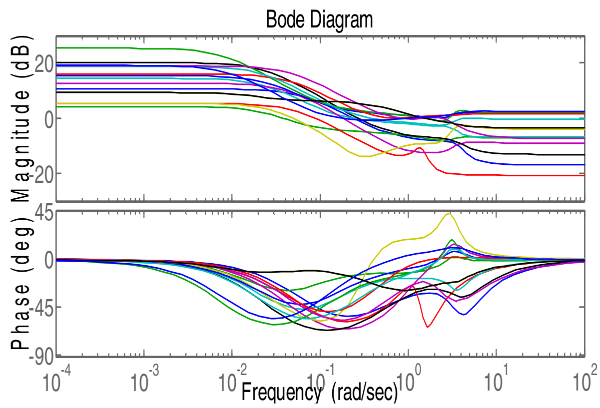

Figure 3. Frequecy response of the steam turbine at different loads

A fourth order ARX (Auto Regressive Exogenous) model without delay is considered to estimate the system by system Identification toolbox of MATLAB. Uncertainty profile is formed by Equation (1) and the model that minimize the amplitude of that, is considered as nominal model.

$$\left| \frac{P(jw)}{P_0(jw)} - 1 \right| \tag{1}$$

The obtained nominal model is a fourth order, stable and minimum phase transfer function as follows:

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$$\frac{1.22S^4+4.41S^3+15.69S^2+14.07S+1.558}{S^4+3.62S^3+14.2S^2+10.59S+.2669} \quad (2)$$

Step responses of the real plant and identified model are shown in Fig. 4. Moreover, the variation of each frequency response estimate from the nominal model can be encapsulated by a multiplicative uncertainty. Assuming that the nominal plant transfer function is P_0, define P the family of possible models of the systems which includes all the experimental frequency response estimates, and the nominal model of the system, by multiplicative uncertainty we consider:

$$\forall P(s) \in \mathrm{P}, P(s) = \left(1+\Delta(s)W(s)\right)P_0(s) \quad (3)$$

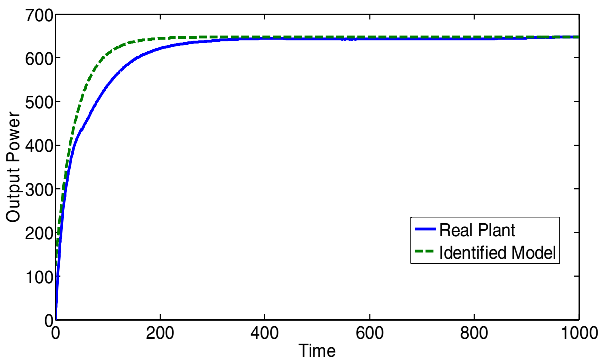

Figure 4. Step response of real plant and identified model at 60% of input pressure

Hence $W(s)$ is a fixed transfer function, called the uncertainty weighting function and Δ is a memory less operator of induced norm less than unity. In this representation $|W_S|$ gives the normalized system variation away from 1 at each frequency:

$$\frac{P(jw)}{P_0(jw)} - 1 = \Delta(jw)W(jw) \quad (4)$$

Hence, since $\|\Delta\| < 1$ then:

$$\left|\frac{P(jw)}{P_0(jw)} - 1\right| \le |W(jw)|, \forall w \quad (5)$$

By plotting the system variations $\left|\frac{P(jw)}{P_0(jw)} - 1\right|$, for all experimental frequency response estimates of the system and by estimating an upper bound to those variations as a transfer function, the multiplicative uncertainty function $W(s)$ will be obtained as illustrated in Fig. 5. The transfer function of uncertainty function is:

$$W(s) = \frac{.75(50s+1)}{(26s+1)} \quad (6)$$

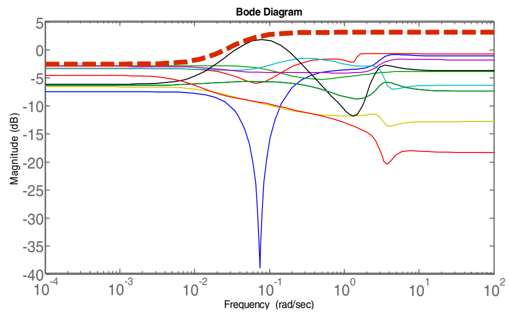

Figure 5. Determining the upper bound for uncertainty

Fig. 6. Shows the block diagram of the generalized plant using multiplicative uncertainty representation, in which P_0 is the nominal model of the system. $W(s)$ is the uncertainty weighting function, $\Delta(s)$ is a memory less operator of induced norm less than unity, which represents the normalized variation of the true system from the model, and C is the controller.

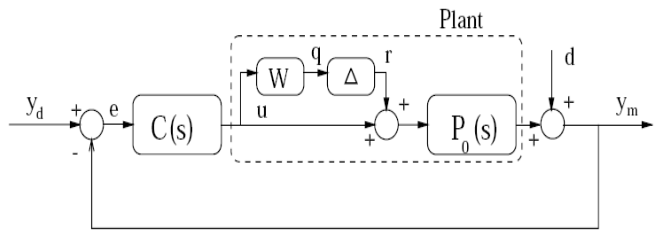

Figure 6. Generelized plant

The control objective can be assumed as robustly stabilizing the system, while maintaining good disturbance attenuation and small tracking error, despite the actuator saturation. Referring to Fig. 6. it is desired to design a controller to trade off minimizing the norm of the transfer function from the disturbance d to the output y (disturbance attenuation), the transfer function from r to q (robust stability), and the transfer function from reference input y_d to the plant input u (actuator limit). Fig. 7. shows the block diagram of the system arranged for the H_∞ frame work. It can be shown that tracking and disturbance attenuation objectives can be expressed as sensitivity S minimization. For multiplicative uncertainty, robust stability is guaranteed if the complementary sensitivity T has a norm less than unity (Zemes small gain theorem) T can be shown to be the transfer function from reference input y_d to the output y.

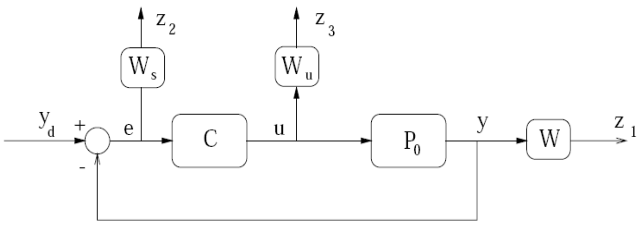

Figure 7. H∞ framework

Weighting functions W_s and W_u are also considered normalizing and assigning frequency content of the performance objective on sensitivity and actuator saturation respectively, and W is the multiplicative uncertainty weighting function. Now, the augmented system has one input y_d, and three outputs z_1, z_2, and z_3, in which the transfer function from the input to the outputs corresponds to weighted complementary sensitivity, weighted sensitivity, and weighted actuator effort, respectively. The objectives now will be reduced to finding the controller $C(s)$ which minimizes the induced norm of the transfer matrix from input y_d to the output vector Z or Find $C(s)$ to minimize $\left\|T_{ydz}\right\|$.

This problem is called a mixed sensitivity problem in the literature, and has optimal and sub optional solution algorithms. Doyl et al provided the sub optimal solution for this problem in 1989, in which $C(s)$ will be assigned such that $\left\|T_{ydz}\right\| < 1$ [11].

The weighting functions for the sensitivity and the actuator effort are denoted by:

$$W_S(s) = \frac{10(.01s+1)}{(100s+1)} \qquad W_u = .95 \tag{7}$$

The reason for choosing W_s in this from is to eliminate steady state error while achieving to a suitable band width. First, bandwidth has been considered to be 0.01 rad/sec, and then the DC gain has been increased while robust stability and performance are not vanished and the suboptimal solution of the mixed sensitivity problem solution remains approximately less than one. The steady state error should be less that 0.1 by this weighting performance transfer function. The amount of the controller effort remains less than $W_u^{-1} = \frac{1}{.95}$ by this control effort weighting function. The suboptimal problem of the mixed sensitivity is:

$$\left\| \begin{matrix} WT \\ W_s S \\ W_u U \end{matrix} \right\|_\infty < 1 \tag{8}$$

The suboptimal problem of the mixed sensitivity problem in Equation (8) was solved using Matlab Robust Toolbox, and the controller was obtained as follows:

$$K = \frac{14.54(s+.8716)(s+.03846)(s+.02611)(s^2+2.728s+11.73)}{(s+8.569)(s+.8964)(s+.09472)(s+.01)(s^2+2.5935s+11.28)} \tag{9}$$

The controller zeros cancel the stable poles of the nominal plant, while the poles shape the closed loop sensitivity function to lie underneath the inverse of the weighting function $W_S(s)$. This robust controller is implemented in closed loop for the turbine nonlinear model. The closed loop system was subjected to a 0.8 PU step input after synchronizing and the set point was decreased to 0.1 PU after 400 seconds and again was increased up to 0.9 PU after 200 seconds and was decreased 0.3 PU after 200 seconds. Fig. 8. Illustrates closed loop system response to this input signal and Fig. 9. shows the magnitude of the control effort. As can be seen the closed loop system response is not good enough especially at premier times and there is a small error between desired and real output. In addition there is some overshoots at starting times and the response is not fast enough. These can be the result of tight constraint on stability. Control effort has considerable overshoots during load variations. μ plot of closed loop system with this controller is shown in Fig. 10. As can be seen from this figure, the magnitude of this plot lies beneath 0 dB at most frequencies and then the closed loop system is enough robust stable.

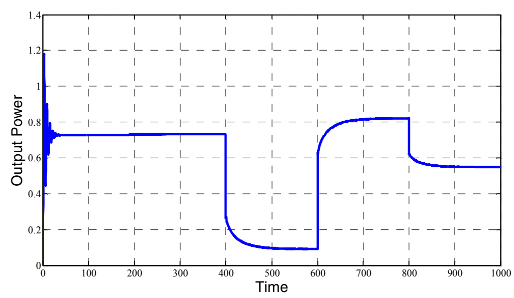

Figure 8. Response of real closed loop system

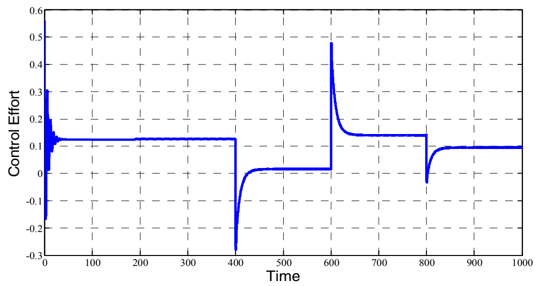

Figure 9. Actuator effort

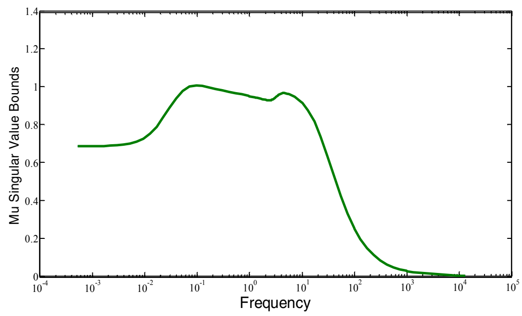

Figure 10. μ plot

IV. ROBUST CONTROLLER DESIGN USING PARALLEL FEEDBACK IDEA

Parallel feedback can be used to decrease nonlinearity dynamic of the turbine system. One of the major specifications of the feedback is linearizing the system behavior. A cascade controller structure in which the turbine loop was closed by a PI controller is proposed in order to reduce the uncertainty. By using this structure, a new controller is designed for the system.

System Identification procedure has been performed again and bode plot of system is shown in Fig. 11. Uncertainty of the system is reduced significantly by using parallel feedback. The nominal model is a fourth order stable and minimum transfer function as follows:

$$\frac{.95S^4 + 15.23S^3 + 85.6S^2 + 249.15S + 260.9}{S^4 + 7.2S^3 + 31.7S^2 + 57.56S + 77.28} \tag{10}$$

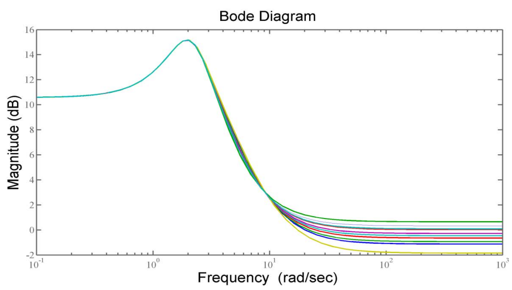

Figure 11. Bode magnitude diagram of closed loop steam turbine with PI controller

By plotting the system variations $\left|\frac{P(jw)}{P_0(jw)} - 1\right|$ Upper bound to those variations as a transfer function, the multiplicative weighting function W_S will be obtained. These variations are illustrated in Fig. 12. According to much reduction of uncertainty after using parallel feedback structure, upper bound of uncertainty is chosen greater than real upper bound, to have a better closed loop robust stability, although it must be beneath 0 dB to have enough flexibility in designing. The transfer function of the weighting function is:

$$W(s) = \frac{.25(50s+1)}{(26s+1)} \tag{11}$$

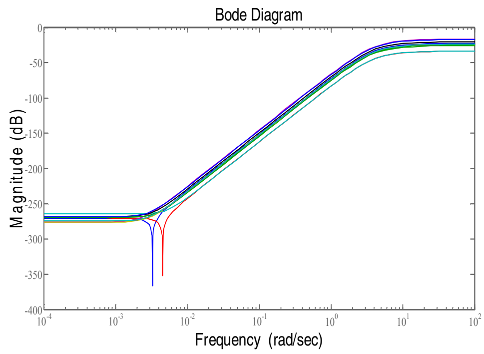

Figure 12. Uncertainty profile for closed loop turbine with PI controller

The weighting functions for sensitivity and actuator are:

$$W_S(s) = \frac{50(.01s+1)}{(100s+1)} \qquad W_u = .95 \tag{12}$$

In choosing of W_S, the bandwidth is considered the same as before and Dc gain was increased to reduce the steady state error. The controller effort amount remains less than $W_u^{-1} = \frac{1}{.95}$ by this control effort weighting function.

The bode magnitudes of $|W_T T|$ and $|W_S S|$ are shown in Fig. 13. and Fig. 14.. As can be seen from these figures, the magnitudes lay beneath 0 dB at most frequencies. Also the magnitude plots of sensitivity and complementary sensitivity functions are shown in Fig. 15. Low magnitude of sensitivity function at low frequencies can bring suitable tracking and performance at steady state. The robust controller was obtained by suboptimal solution of the mixed sensitivity problem as follows:

$$K = \frac{57.17(s+.03846)(s^2+2.012s+4.654)(s^2+5.19s+16.6)}{(s+65.19)(s+.00997)(s^2+.3961s+.4277)(s^2+5.165s+16)} \tag{13}$$

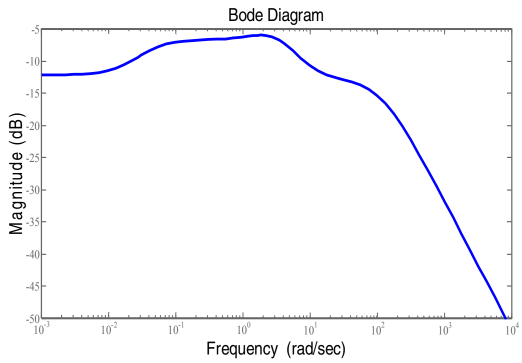

Figure 13. Bode magnitude of WT*T

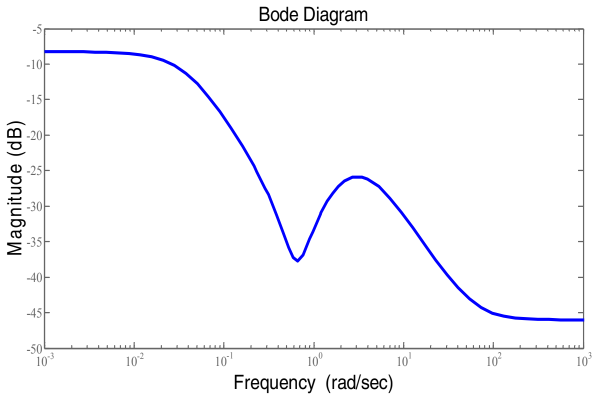

Figure 14. Bode magnitude of WS*S

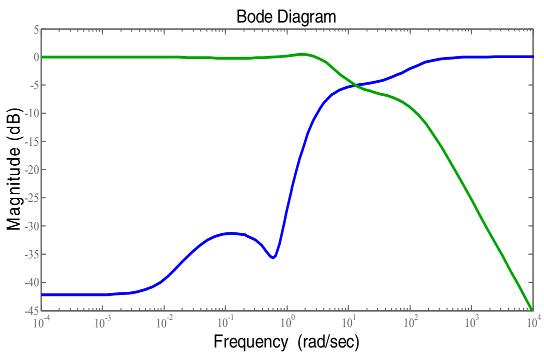

Figure 15. Bode magnitude of sensitivity and complementary sensitivity function

Fig. 16. illustrates step responses of the closed loop system for 50 uncertain models and Fig. 17. illustrates the bode plot of the controller. Singular value plots of the robust stability, performance, and actuator effort are shown in Fig. 18. and all of them are beneath 0 dB.

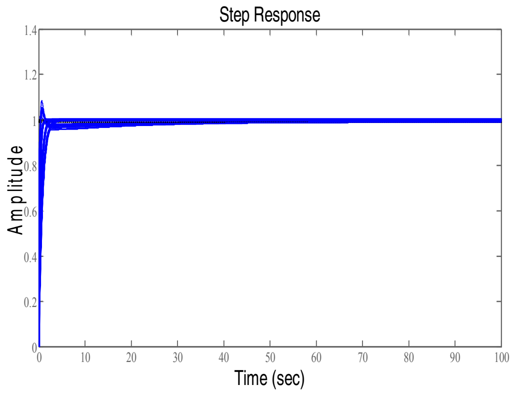

Figure 16. Step response of closed loop system for 50 uncertain models

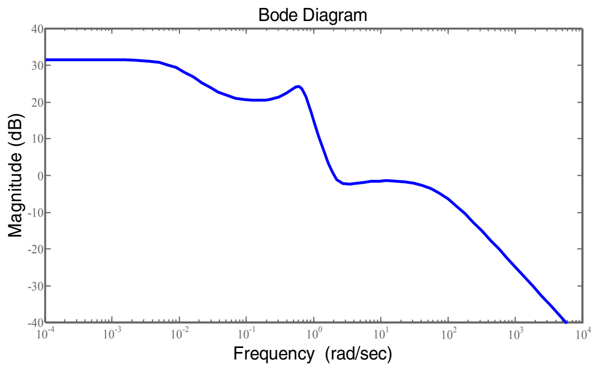

Figure 17. Bode magnitude of robust controller with parallel feedback idea

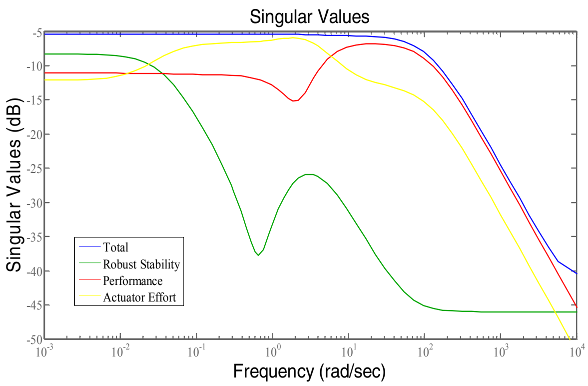

Figure 18. Singular value plot of closed loop system

This robust controller is implemented in closed loop for the turbine nonlinear model in a cascade structure. The closed loop system was subjected by the same input as before. The performance of the closed loop system by proposed controller and a classic PI controller was compared. As can be seen in Fig. 19., the closed loop system achieves a better performance in terms of tracking and response speed, with the proposed controller. The control effort magnitudes are shown in Fig. 20. for two controllers. Using proposed controller damps the overshoots of the actuator that can increase effective life of instruments in the plant.

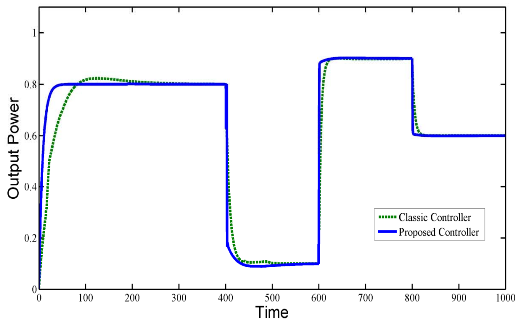

Figure 19. Response of real closed loop system with paralle feedback idea

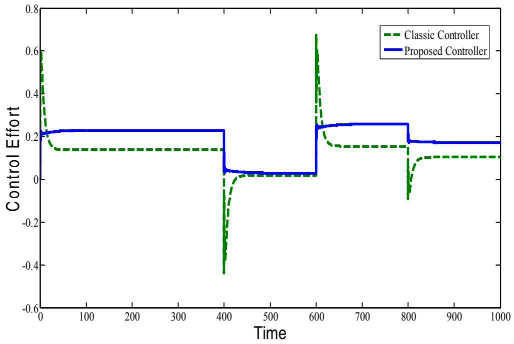

Figure 20. Control effort for proposed controller and PI controller

V. COCCLUSION

In this paper continuous time model of Nekka steam turbine at various loads has been obtained by performing of identification procedures. After determining the upper bound for uncertainty and choosing a performance weighting function with the bandwidth of .01 rad/s, a robust controller was designed and implemented for the turbine nonlinear model. However, the closed loop performance was not suitable, and therefore, a parallel feedback structure is proposed to reduce the uncertainty of the system. A new robust controller has been designed for the cascaded system. Simulation results shows that the closed loop system with the proposed controller structure has a suitable performance in terms of tracking, speed of response, and damping of oscillations.

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