ROBUST CONTROLLER DESIGN FOR LOAD FREQUENCY CONTROL IN POWER SYSTEMS USING STATE-SPACE APPROACH

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ABSTRACT:

In this paper a robust governor has been designed using H_∞ techniques to replace the conventional governor of the steam turbine of the power system to regulate the frequency of the power grid. The robust governor is synthesized using state-space approach with time variations, neglected dynamics, and constant main steam pressure are considered in the design process. The proposed approach ensures internal stability, satisfying both frequency and time domains requirements, and obtaining minimal performance H_∞-norm of the closed-loop system in one burden. The simulations are carried out using MATLAB and the results show that the overall system output performance can be improved using the proposed H_∞ robust governor.

الخلاصة

في هذا البحث تم تصميم حاكم نشيط بإستخدتم تقنيات ال (H_∞) ليستبدل الحاكم التقليدي لمنظومة التوربين في منظومات الطاقة الكهربائية لتنظيم التردد الخاص بالشبكة الكربائية. المسيطر النشيط تم تصميمه بإستخدام طريقة فضاء الحالة مع الاخذ بنظر الاعتبار التغيرات الزمنية، الديناميك المهمل، ضغط ثابت للبخار المتولد من المرجل. الطريقة المقترحة تضمن الاستقرارية الداخلية و وتحقق كلاً من متطلبات مجالي الزمن و التردد وتحصل على أقل (H_∞-norm) للنظام المغلق في نفس الوقت. النتائج نفذت إستخدام برنامج MATLAB وأظهرت بأن الاداء الكلي للمنظومة يمكن أن يتحسن بإستخدام الحاكم النشيط المقترح.

KEYWORDS: robust control, load frequency control, steam turbine, H_∞-norm, system uncertainty, load disturbance.

BACKGROUND AND MOTIVATION

Modern power systems are highly complex and non-linear and their operating conditions can vary significantly over a wide range. Power system stability can be defined as that property of a power system that enables it to remain in state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance [1, 2]. The quality of power supply must meet certain minimum standard requirements with regard to the following factors:

- Constancy of frequency.
- Constancy of voltage.
- Level of reliability.

The main concern in this work is regarding the first factor mentioned above. Most universal method of electric generation is accomplished using thermal generation, and the most common machine for this production is the steam turbines. In the world most of the generation is powered by steam-turbine-driven generators. The size of these generating units has increased over time and the steam used in electric production is produced in steam generators or boilers using either fossil or nuclear fuels as primary energy sources [2].

Ideally, the load must be fed at constant voltage and frequency at all times. In practical terms this means that both voltage and frequency must be held within close tolerances so that the consumer's equipments may operate satisfactorily. For example, reduction of the system frequency of only a few hertz may lead to stalling of the motor loads on the system [2]. Subsequent large change in the system frequency might cause cascade trips of the generating power plants and results in system breakup. Thus it can be accurately stated that the power system operator or automatic control system must maintain a very high standard of continuous electrical service [2].

Poor balancing between generated power and demand can cause the system frequency to deviate away from the nominal value, and create inadvertent power exchanges between control areas. To avoid such a situation, Load Frequency Controllers (LFC) are designed and implemented to automatically balance between generated power and the demand power in each control area [1, 3, 4].

The problem of load frequency control has been investigated by many researchers. In [5] speed governors have been designed based on PID techniques with different philosophies because of its simplicity and ease of implementation. Fuzzy sliding mode controller for LFC has been designed in [6] to account for the system's parameters variations and the governor backlash. Genetic Algorithm (GA) is a global search optimization technique. The researchers in [7] used GA for tuning the control parameters of the Proportional-Integral (PI) control subject to the H_∞ constraints in terms of LMI. Modern control techniques have been reported in [8, 9] in which a load frequency controller for power systems has been designed using LQR techniques. The work in [10] investigated the design problem or robust load frequency controller using LMI methods for solving the H_∞ control problem.

This paper is organized as follows: in section 2 a brief introduction to the robust control theory and H-infinity techniques is given. Section 3 describes the mathematical modeling of the steam turbine system and the design objectives. Section 4 presents the design procedure of the robust governor and Section 5 is devoted to the performance evaluation and simulation results. Collusions are given in section 6.

ROBUST CONTROL AND H-INFINITY TECHNIQUES

Central to the development of feedback control theory has been the notion of uncertainty. Uncertainty refers to the differences or errors between models and reality. It can be defined as discrepancy between the physical plant and the mathematical model used for controller design. A good model should be simple enough to facilitate design, yet complex enough to give the engineer confidence that designs based on the model will work on the true plant.

For a scalar stable transfer function $G(s)$, the H_∞-norm is simply the peak value of $|G(j\omega)|$ as a function of frequency (i.e. maximum of Bode plot) [11, 12, 13]:

$$\|G(s)\|_\infty = \sup_\omega |G(j\omega)| \quad (1)$$

Where sup is the supremum or the least upper bound, it is the same as max value and it is used here instead of max because the maximum may only be approached as $\omega \to \infty$ and may therefore not actually be achieved. The H_∞ stands for **Hardy Space** which is a functional space containing all analytic and bounded transfer functions in the RHP and the symbol ∞ implies that it is designed to accomplish minmax restrictions in the frequency domain.

The shaping of a multivariable transfer function is based on the idea that a satisfactory definition of gain (range of gain) for matrix transfer function is given by the singular values σ of the transfer function. By multivariable transfer function shaping, therefore it is meant that the shaping of singular values of appropriately specified transfer functions such as the loop transfer function $L = KG$ or possibly one or more closed-loop transfer functions [14,15]. Two essential objectives are required for the closed-loop system, these are [15]:

- For disturbance rejection we have to make $1/\bar{\sigma}(S) \geq |W_P|$, where W_P is the performance bound.
- While for robust stability against a multiplicative perturbation $G_p = G(I + \Delta)$ we have to make $\bar{\sigma}(T) \leq |W_I^{-1}|$ where W_I^{-1} is the robustness bound.

The two mentioned requirements cannot all be met at the same time. Feedback is therefore a tradeoff over frequency of conflicting objectives.

Weighted Performance and Weighting Filters Selection Criteria

The performance objectives of the feedback system can usually be specified in terms of requirements on the sensitivity S and /or complementary sensitivity T functions or in terms of some other closed-loop transfer functions like control sensitivity function R as defined below:

$$S = \frac{c}{d} = \frac{1}{1+L} \quad (2)$$

$$R = \frac{u}{r} = \frac{K}{1+L} = K\,S \quad (3)$$

$$T + S = I \Rightarrow T = \frac{c}{r} = I - S = \frac{L}{(1+L)} \quad (4)$$

To achieve the two essential requirements mentioned early, the following have to be satisfied [14,15]:

- For disturbance rejection minimize $\bar{\sigma}(S)$ over the low frequency range. To do this one could select a weighting filter $W_P(s)$ that has low-pass filter characteristics with bandwidth equal to the bandwidth of the disturbance. The optimal robust control problem is then solved by finding a stabilizing controller that minimizes $\|W_P S\|_\infty$.
- The $\bar{\sigma}(T)$ needs to be minimized as large as possible at high frequencies to account for unstructured uncertainties that appear in that frequency range. To achieve this goal, a weighting filter $W_I(s)$ has to be chosen such that it has high magnitude at high frequencies and low at low frequencies with the condition that $\|W_I T\|_\infty$ is minimized.
- Finally, the control sensitivity R should be kept at low values to limit the magnitude of the control signal u to prevent saturation of the actuators. To get this done, the control sensitivity R has to be reshaped with a weighting filters such that $\|W_U R\|_\infty$ is minimized in the specified frequency range.

The minimization process to the closed-loop transfer functions is achieved at different frequency regions especially for S and T to keep the equation $S + T = I$ valid over the entire frequency range. This can be done via the selection of corresponding weighting filters with different frequency characteristics as explained above. From the above discussion the requirements for the performance become [14,15,16]:

$$\|W_P S\|_\infty \le 1 \Rightarrow \bar{\sigma}(S(j\omega)) \le \bar{\sigma}(W_P^{-1}(j\omega))$$
$$\|W_I T\|_\infty \le 1 \Rightarrow \bar{\sigma}(T(j\omega)) \le \bar{\sigma}(W_I^{-1}(j\omega)) \quad (5)$$
$$\|W_U R\|_\infty \le 1 \Rightarrow \bar{\sigma}(R(j\omega)) \le \bar{\sigma}(W_U^{-1}(j\omega))$$

The selection of the weighting filters is not an easy task for a specific design problem and often involves ad hoc, and fine tuning. It is very hard to give a general formula for the weighting filters that will work in every case. Finally the selection of the uncertainty weighting filter depends on the dynamics of the system and the nominal model chosen [14,15].

There are many ways in which feedback problems can be casted as H_∞ optimization problem, one of them is afforded in **Fig. 1**.

The closed-loop transfer functions from w to z is given by the Linear Fractional Transformation (LFT) [17,18]:

$$z = T_{zw}\, w = F_l(P,K)\, w \quad (6)$$

$$T_{zw} = F_l(P,K) = P_{11} + P_{12}K(I - P_{22}K)^{-1} P_{21} \quad (7)$$

Where P is the open-loop generalized plant that includes the plant transfer function in addition to the weighting filters and is the H_∞ controller K. It should be said that the H_∞ algorithms, in general, find a suboptimal controller, that is, for a specified γ a stabilizing controller is found for which $\|F_l(P,K)\|_\infty < \gamma$. If an optimal controller is required then the algorithm can be used iteratively, reducing γ until the minimum is reached within a given tolerance [14,15,18].

The standard H_∞ suboptimal control problem for **Fig. 1** is to find all stabilizing controllers $K(s)$ which minimize [14,15,18]:

$$\|T_{zw}\|_\infty = \|F_l(P,K)\|_\infty = \max_{\omega} \bar{\sigma}(F_l(P,K)(jw)) \quad (8)$$

For the general control configuration of Fig. 1, there exist a stabilizing controller $K(s)$ such that $\|F_l(P,K)\|_\infty < \gamma$ if and only if [18,19,20]:

(i) $X_\infty \ge 0$ is a solution to the following algebraic Riccati equation:

$$A^T X_\infty + X_\infty A + C_1^T C_1 + X_\infty(\gamma^{-2} B_1 B_1^T - B_2 B_2^T) X_\infty = 0 \quad (9)$$

Such that

$Re(\lambda_i[A + (\gamma^{-2} B_1 B_1^T - B_2 B_2^T) X_\infty]) < 0, \forall i$; and

(ii) $Y_\infty \ge 0$ is a solution to the following algebraic Riccati equation:

$$A Y_\infty + Y_\infty A^T + B_1 B_1^T + Y_\infty(\gamma^{-2} C_1^T C_1 - C_2^T C_2) Y_\infty = 0 \quad (10)$$

Such that

$Re(\lambda_i[A + Y_\infty(\gamma^{-2} C_1^T C_1 - C_2^T C_2)]) < 0, \forall i$; and

(iii) $\rho(X_\infty Y_\infty) < \gamma^2$

Moreover, when these conditions hold, one such controller $K(s)$ is given with the following state-space representation [14,15,16,17,20]:

$$K_{sub}(s) \triangleq \left[\begin{array}{c|c} A_\infty & -Z_\infty L_\infty \\ \hline F_\infty & 0 \end{array}\right] \quad (11)$$

$$A_\infty = A + \gamma^{-2} B_1 B_1^T X_\infty + B_2 F_\infty + Z_\infty L_\infty C_2$$
$$F_\infty = -B_2^T X_\infty \;,\; L_\infty = -Y_\infty C_2^T \;,\; Z_\infty = (I - \gamma^{-2} Y_\infty X_\infty)^{-1}$$

STEAM TURBINES AND SPEED GOVERNING SYSTEM

A steam turbine converts stored energy of high pressure and high temperature steam into mechanical energy, which is in turn converted into electrical energy by the generator. The heat source for the boiler supplying the steam may be a nuclear reactor or a furnace fired by fossil fuel (coal, oil, or gas) [1, 21].

Steam turbines normally consist of two or more turbine sections or cylinders coupled in series. Most units placed in service in recent years have been of the tandem-compound design, in which, the sections are all on one shaft, with a single generator. Typical configuration of tandem-compound steam turbine with single reheat is shown in **Fig. 2**.

A typical mechanical-hydraulic speed governing system consists of a Speed Governor (SG), a Speed Relay (SR), a Hydraulic Servomotor (SM), and Governor-Controller Valves (CVs). In steam turbine-generator system, the governing is accomplished by a speed transducer, a comparator, and one or more force-stroke amplifiers. **Fig 3** depicts the complete system block diagram of a steam turbine generator [2].

The transfer function of each individual block is derived as follows [1,2,4,21,22]:

Speed Governor (SG):

$$S_G = \frac{1}{R} \tag{12}$$

Where R is the steady-state speed regulation. The value of R determines the steady-state speed load characteristic of the generating unit.

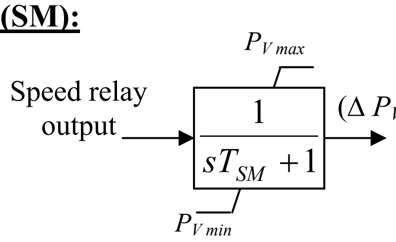
Speed Relay (SR):

$$S_R(s) = \frac{1}{sT_{SR} + 1} \tag{13}$$

Where T_{SR} is the time constant of the speed relay.

Servo Motor (SM):

$S_M(s) \equiv$



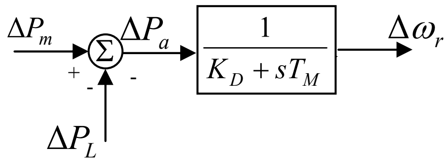
Where T_{SM} is the time constant of the servomotor.

Steam Turbine (ST):

$$S_T(s) = \frac{\Delta P_m}{\Delta P_V} = \frac{(F_{HP}(sT_{CO}+1)(sT_{RH}+1) + F_{IP}(sT_{CO}+1) + F_{LP})}{(sT_{CH}+1)(sT_{CO}+1)(sT_{RH}+1)} \tag{14}$$

Where T_{CO}, T_{RH}, T_{CH} are the time constants for the cross over, reheater, and steam chest respectively.

Machine Dynamics (MD):



Where T_M is the mechanical starting time.

ΔP_m is the incremental change of the turbine mechanical power.

ΔP_L is the incremental change of load power.

ΔP_a is the incremental change of accelerating power.

$\Delta \omega_r$ is the deviation of the angular speed of the synchronous generator.

Speed Disturbance Spectrum (SD)

$$W_{D3}(s) = \frac{1}{s + 2\pi f_o} \tag{15}$$

The model of the complete steam turbine system has been derived with typical values of parameters of the model shown in **Fig. 3**. This model is applicable to a tandem-compound single reheat turbine of fossil-fuelled units are listed in **Table 1** [1,2,22].

1. H_∞ CONTROLLER DESIGN FOR THE UNCERTAIN STEAM TURBINE SYSTEM: A STATE-SPACE APPROACH

This section summarizes the design procedure of the H_∞ robust governor design for the steam turbine system based on state-space techniques in which the system will be represented by four system matrices $\{A, B, C, D\}$.

For steam turbine system, the design requirements that have to be satisfied are summarized as follows:

- ***Time-domain requirements:***
  - Good and swift disturbance rejection with steady-state error less than $0.2\,\%$.
  - The closed-loop system is stable at all operating conditions.
  - Undershoot of the output frequency deviation is as minimum as possible.
  - Control signal (u) lies in the range [0,1] in response to step load change.

- ***Frequency-domain requirements:***
  - Phase margin > 40^o.
  - Gain margin > 10 dB.
  - High frequency roll-off to the controller.

In designing a robust governor the parameter variations have to be taken into consideration in the design process since the variations are a common phenomenon in many practical applications, one of them is the steam turbine system.

This can be done by designing the H_∞ robust controller for the nominal model $G_{nom}(s)$ rather than the original one $G(s)$. Usually the nominal model $G_{nom}(s)$ is of a transfer function which is simpler than the original transfer function $G(s)$ or perturbed one $G_P(s)$. One possible proposed choice of the nominal model for the steam turbine system is:

$$G_{nom}(\mathrm{s}) = G_{1nom}(s)\cdot G_{2nom}(s) = \frac{(F_{HP}\,T_{RH}s+1)}{(T_{CH}s+1)\,(T_{RH}s+1)}\cdot\frac{1}{(T_M s+K_D)} \qquad (16)$$

Where the dynamics that represents the speed relay $SR(s)$, servo motor $SM(s)$, and the crossover piping in the turbine transfer T_{CO} have been neglected as they have very small time constants. These neglected high frequency dynamics will be represented as an output multiplicative uncertainty in the design stage, where the original model $G(s)$ will be replaced by a nominal model $G_{nom}(s)$ together with uncertainty filter $W_I(s)$ usually of finite and low order. In addition, real perturbations are added to the system by allowing specific parameters to vary in their ranges. In this model two parameters are assumed to be uncertain. With the aid of **Table 1**, the characteristics of these two uncertain parameters are listed in **Table 2**.

At this end the nominal model $G_{nom}(s)$ has been chosen based on simplification in the original model $G(s)$. With perturbations added to the two parameters mentioned above, the nominal model becomes:

$$G_{1nom}(s) = \frac{(1+sF_{HP}\overline{T}_{RH})}{(1+s\overline{T}_{CH})\,(1+s\overline{T}_{RH})} \qquad (17)$$

$$G_{2nom}(s) = \frac{1}{(T_M s+K_D)} \qquad (18)$$

$$G_{nom}(\mathrm{s}) = G_{1nom}(s)\cdot G_{2nom}(s) = \frac{(2.1s+1)}{(0.25s+1)\,(7s+1)}\cdot\frac{1}{(8s+2)} \qquad (19)$$

While the perturbed transfer function $G_P(s)$ is given by:

$$G_P(s) = \frac{1}{0.1s+1}\cdot\frac{1}{0.2s+1}\cdot \frac{0.3(0.4s+1)(T_{RH}\mathrm{s}+1)+0.4(0.4s+1)+0.3}{(T_{CH}s+1)(0.4s+1)(T_{RH}s+1)}\cdot\frac{1}{8s+2} \qquad (20)$$

Where T_{CH} and T_{RH} are uncertain, their ranges are defined in table 1 and, $\overline{T}_{CH}$,$\overline{T}_{RH}$ are the nominal values of their respective variables. Their values can be obtained from table 5.1. Based on the above analysis, the next step is to design the uncertainty filter $W_I(s)$ which represents the neglected dynamics as well as the variations in T_{CH} and T_{RH}. The uncertainties of these two parameters will contribute in the design of the uncertainty weighting filter $W_I(s)$.

Now, the H_∞ design procedure will be carried out on the nominal plant $G_{nom}(s)$ together with the uncertainty filter $W_I(s)$ that compensates for the modeling errors (neglected dynamics plus parameter perturbations).

With output multiplicative uncertainty has been incorporated into the system, the open-loop generalized plant will be represented by $P(s)$:

$$P(s) = \left[\begin{array}{ccc|c} 0 & 0 & 0 & W_I G_1 \\ 0 & 0 & 0 & W_U \\ W_p G_2 & -W_p G_2 & W_p W_{D3} & W_p G_1 G_2 \\ \hline -G_2 & G_2 & -W_{D3} & -G_1 G_2 \end{array}\right] := \left[\begin{array}{c|cc} A & B_1 & B_2 \\ \hline C_1 & D_{11} & D_{12} \\ C_2 & D_{21} & D_{22} \end{array}\right] \quad (21)$$

While the weighted closed-loop transfer function matrix T_{zw} is given by:

$$T_{zw} = \begin{bmatrix} -W_I T & W_I T & -W_I G_1 KS\, W_{D3} \\ -W_U K\, G_2 S & W_U K G_2 S & -W_U KS\, W_{D3} \\ W_P G_2 S & -W_P G_2 S & W_P S W_{D3} \end{bmatrix} \quad (22)$$

The block diagram of the augmented plant $P(s)$ including the performance and uncertainty weighting filters ($W_P(s)$, $W_U(s)$ and $W_I(s)$) together with plant is shown in Fig. 4, where an output multiplicative uncertainty is assumed in the system as indicated by the uncertainty weight $W_I(s)$ and the input d_1.

Selection of the Weighting Filters

Two kinds of weighting filters have been designed in the H_∞ optimization process:

- **Performance weighting filters:** Two performance weighting filters have been used. The performance weighting filter $W_P(s)$ reflects the requirements of disturbance rejection. While the second weighting filter $W_U(s)$, is included to limit the value of the control signal (u) to avoid the saturation of the actuators. After deep analysis it is found that the following weighting filters that are suitable for the problem at hand [23]:

$$W_P(s) = \frac{s+0.29}{s+2.9*10^{-6}} \quad , \quad W_U(s) = \frac{1}{10}$$

- **Uncertainty weighting filter**: This weighting filter represents the neglected dynamics in the model in addition to the parametric uncertainties in the variables T_{CH} and T_{RH} and is given as follows [23]:

$$W_I(s) = W_{I_1}(s) = \frac{4500\,\mathrm{s} + 1067}{\mathrm{s} + 3333}$$

Up to this point all the weighting filters have been designed. Applying the H_∞ design procedure to the generalized plant $P(s)$, the optimization process ends with the following results [23]:

- $\gamma_{\min} = 0.9631$ and the H_∞-norm of the closed-loop transfer function is $T_{zw}(s) = 0.963054$.
- The H_∞ controller is suboptimal, strictly proper, and of 6th order:

$$K(s) = \frac{41176293.2898\,(s+3333)\,(s+4)\,(s+2.975)\,(s+0.2588)\,(s+0.1429)}{s\,(s+5.41*10^4)\,(s+6.499*10^4)\,(s+66.89)\,(s+0.959)\,(s+0.4825)}$$

SIMULATIONS AND RESULTS

In this section the time and frequency domain simulations have been carried out on the closed-loop configuration of the steam turbine system as shown in **Fig. 5** and have been done using MATLAB software.

Where,

$K(s)$ = the designed H_∞ robust governor $K(s)$

$G_1(s)$ = $SR(s)*SM(s)*ST(s)$,

$G_2(s)$ = $MD(s)$.

ΔP_L = Load disturbance signal,

ΔP_m = Output Mechanical power of the turbine,

$\Delta\omega_r$ = Output frequency deviation ($\Delta\omega_r = 0$ if $\Delta P_L = 0$),

d_3 = Speed disturbance signal,

u = Control signal (output of the governor),

The frequency response of the compensated system $G(s)*K(s)$ is drawn in **Fig. 6**. The controller has an integrating action as planned for which tends to damp the low frequency disturbances as it is clear in the time response simulations. Also the controller has a high frequency roll-off of 20 dB/decade. The controller gives a very good phase margin about 72.42^{o} with 3.908 rad/sec phase crossover frequency and gain margin of about 35 dB with gain crossover frequency of 0.26 (rad/sec).

Since all the roots of $1+G(s)*K(s)$ lie in the open left half s-plane, then nominal stability is guaranteed. Both robust stability and nominal performance tests are illustrated in **Fig. 7**. The figure confirms that the nominal performance condition has been satisfied. As seen the bound $1/W_P$ covers the sensitivity S with wide gap between them. Since the uncertainty in the system is unstructured and is modeled in multiplicative form, the verification of the robust stability is performed by plotting the singular values of T and comparing it with the frequency response of the bound $1/|W_I|$. This is shown in **Fig. 7**. RP is automatically satisfied when the subobjectives of NP and RS are satisfied.

To check the stability of the system against the variations of the system parameters, the two uncertain parameters has been set to two extreme values as depicted in **Fig. 8** where the transient behavior of the output speed deviations due to load disturbance step of 0.02 p.u ($\Delta P_L = 0.02$ p.u) is plotted. As seen in the figure, the system exhibits clear performance degradation due to the parametric perturbations of the uncertain variables. But, evidently the system ensures stability even when the uncertain parameters vary over their entire range.

The nature of the generating unit with reheat turbine when subjected to 0.04 p.u step change in the load (load disturbance) is illustrated in **Fig. 9**. These responses have been computed by using the typical parameters listed in table 1. Values shown are in per unit of the step change. As can be seen from the figure, the increase in P_L causes the frequency to decay at a rate determined by the inertia of rotor. As the speed drops, the turbine mechanical power begins to increase. This in turns causes a reduction in the rate of decrease of speed with undershoot of $8.5*10^{-3}$, and then an increase in speed when the turbine power is in excess of the load power(this starts beyond 10.7 sec). The speed will ultimately return to its reference value within 23 sec settling time and steady-state error of about 0.17% and the steady-state turbine power is increased by an amount equal to the additional load.

CONCLUSION

The robust governor has been designed and the simulations had showed that the closed-loop of the steam turbine system with this robust governor exhibits a very good results and it satisfy both the time and frequency domain requirements. The robust governor designed by the H_∞ techniques based on the state-space approach ensures both robust stability and robust performance of the closed-loop system against parametric variations and neglected dynamics for the steam turbine system.

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LIST OF SYMBOLS

$F_l(P,K)$	lower linear fractional transformation
H_∞	subspace containing all analytic and bounded transfer functions in the
$Re(x)$	real value of the complex number x
$\Vert G\Vert_\infty$	H-infinity norm of G
sup	is the supremum or the least upper bound
$\rho(G)$	maximum eignvalue of the matrix G
$\sigma_i(G)$	i-th singular values of the matrix G
$\bar{\sigma}$	maximum singular values of the matrix G
λ	eignvalue of the matrix G
γ	solution of the H_∞ optimization
X_∞	solution of the riccati equation
Y_∞	solution of the riccati equation
T_{zw}	weighted closed-loop transfer function

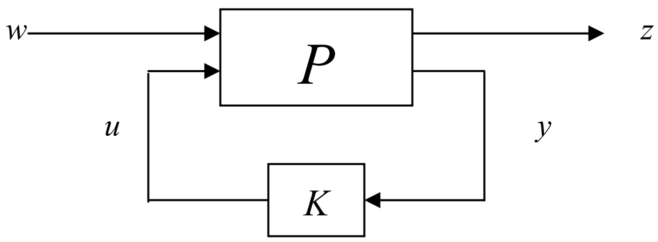

Figure 1: General control configuration.

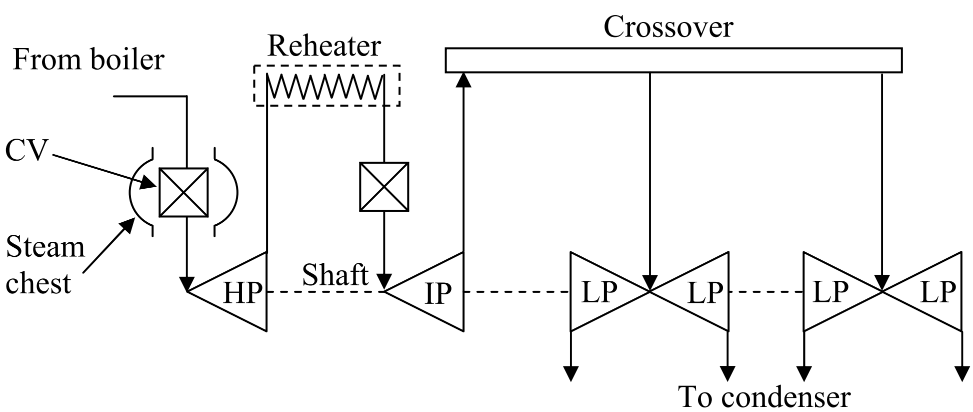

Figure 2: Tandem-compound single reheat steam turbine Configuration.

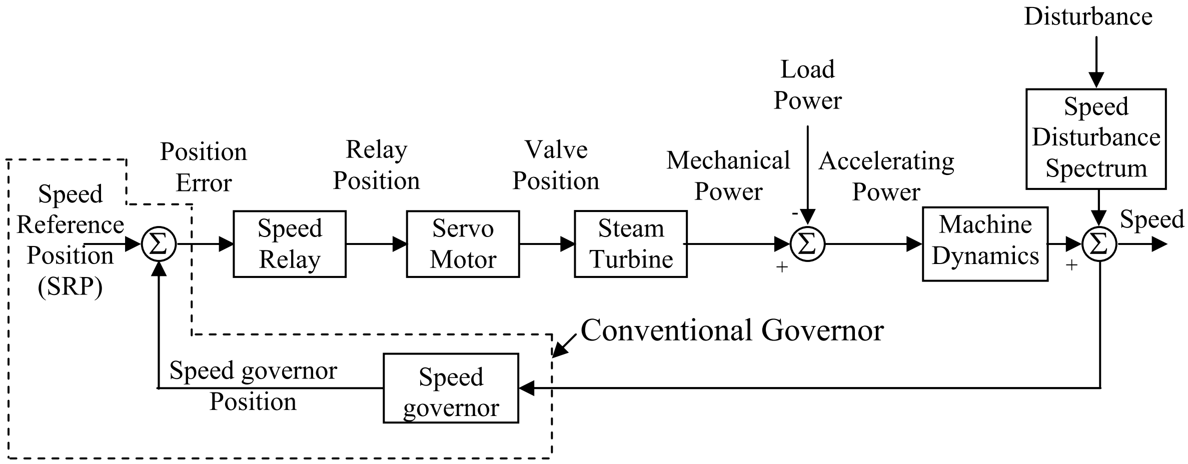

Figure 3: Block diagram of steam turbine control system.

Table 1: Description of the Steam Turbine System Parameters.

Parameter	Description	Value	Unit
K_D	Damping factor = torque (pu) / speed (pu)	2	pu
T_M	Mechanical starting time	8	sec
F_{IP}	IP turbine power fraction	0.4	-
F_{LP}	LP turbine power fraction	0.3	-
F_{HP}	HP turbine power fraction	0.3	-
T_{CO}	Crossover time constant	0.4	sec
T_{SR}	Speed relay time constant	0.1	sec
T_{SM}	Servomotor time constant	0.2	sec
T_{CH}	Steam chest time constant	0.25	sec
T_{RH}	Reheater time constant	7	sec
$P_{V\,max}$	Maximum valve position	1	pu
$P_{V\,min}$	Minimum valve position	0	pu
f_o	Speed disturbance bandwidth	0.5-2	Hz

Table 2: Specifications of uncertain parameters.

Parameter	Nominal symbol	Nominal Value/sec	Range/sec
Steam Chest time (T_{CH})	$\overline{T}_{CH}$	0.25	0.1-0.4
Reheat Time (T_{RH})	$\overline{T}_{RH}$	7	3-11

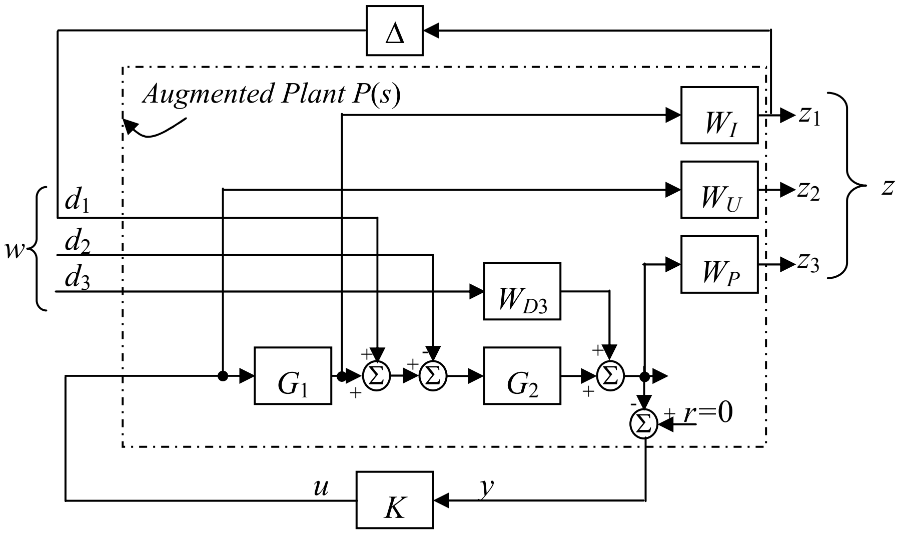

Figure 4: Augmented Plant for the H$_\infty$ Control Problem.

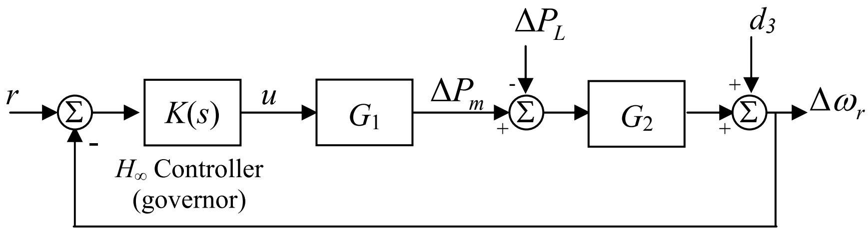

Figure 5: Closed loop of the steam turbine system.

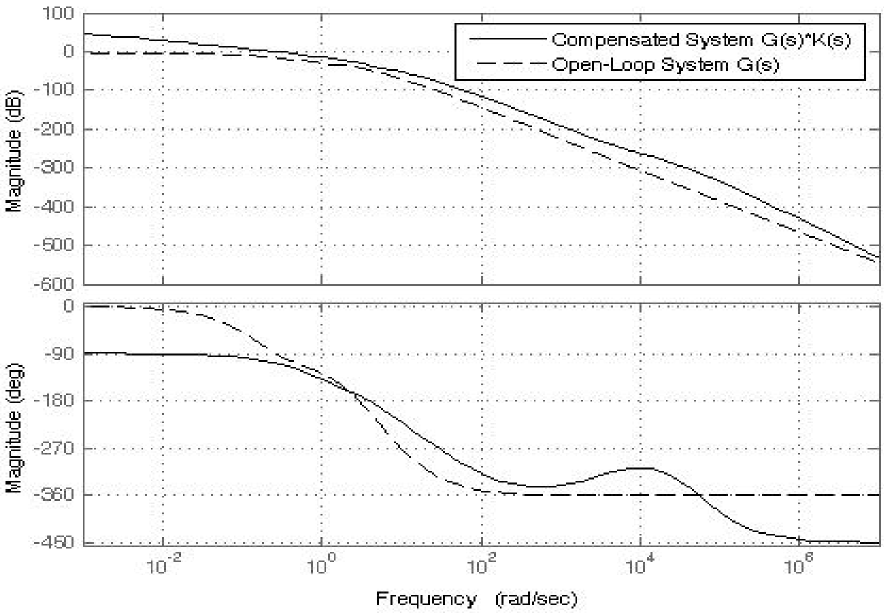

Figure 6: Frequency response of the system

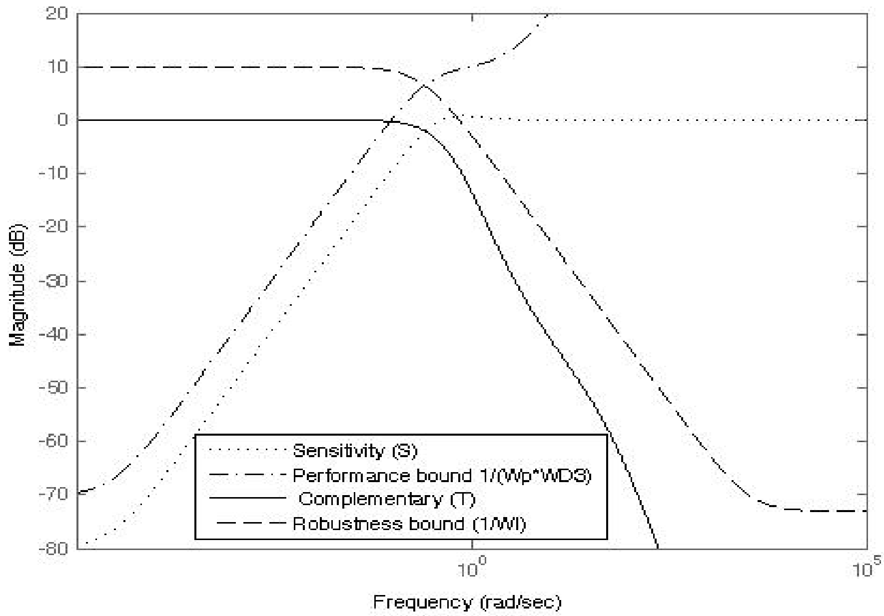

Figure 7: Singular values of *S, T,* and their Performance bounds.

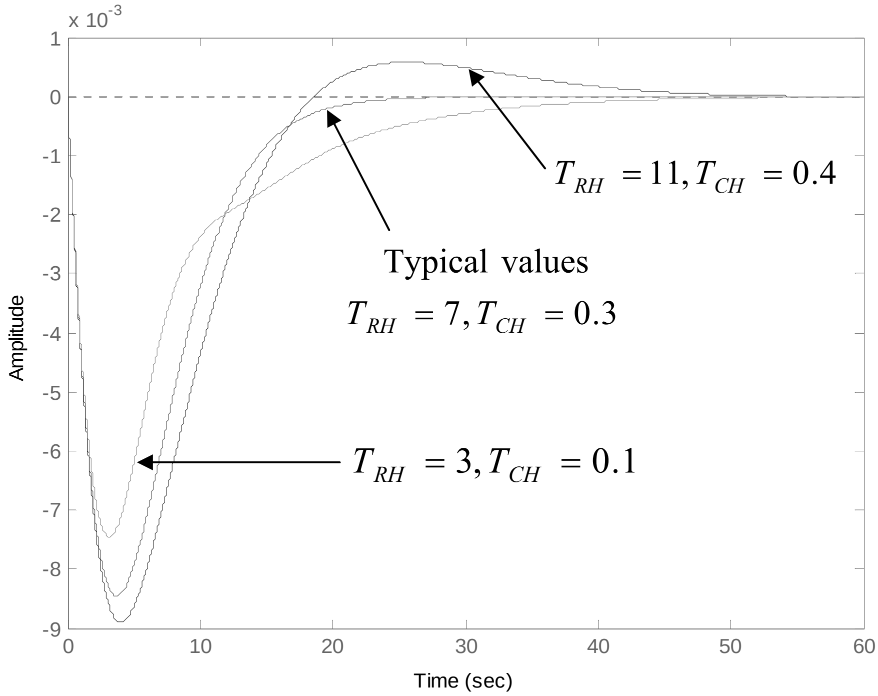

Figure 8: Response of $\Delta\omega_r$ for extreme values of the uncertain parameters T_{RH} and T_{CH}.

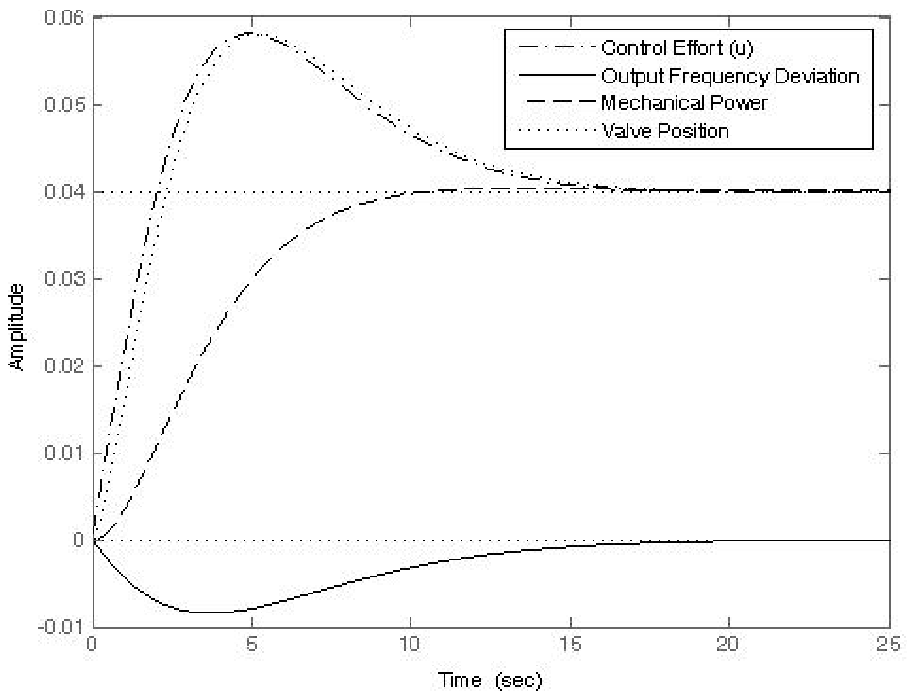

Figure 9: Transient response of the closed-loop system to a small step increase ΔP_L.