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Robust Stability based PI Controller Design with Additive Uncertainty Weight for AGC (Automatic Generation Control) Application

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Abstract:

Robust control has emerged as a new field of control engineering research that primarily deals with obtaining system robustness in presences of uncertainties. In this paper, a graphical design method for obtaining the entire range of PI controller gains that robustly stabilize a non reheat AGC plant in presence of additive uncertainty is discussed. This design method mainly depends on the frequency response of the system which can serve to reduce the complexities involved in plant modelling. We have applied our design method to a single area non-reheat steam generation unit. The results were found satisfactory and robust stability was achieved for the said plant.

Keywords: PI controller, robust control, Automatic generation control (AGC), Uncertainty, Stability.

I. INTRODUCTION

Modern control system engineering primarily deals with improving manufacturing processes, efficiency of energy use, advanced automobile control, chemical processes, traffic control systems, and robotic systems, among others [6]. Integrating the basics of classical control, and the flexibilities offered by robust control, a new era of stable, sustainable, and reliable control systems can be designed. Plant parametric uncertainties always tend to haunt production output and prevent optimal use of available resources. Robust control is concerned with obtaining control systems that are indifferent to model/plant mismatch. Extensive research has been carried out in controller design methods to obtain stability for plants with uncertainties. Controller design methods for Automatic Generation Control (AGC), a vital component of power system frequency control and generation scheduling, is being widely studied [3-7]. In this paper, a graphical design method to obtain PI controller gains to achieve robust stability for a non reheat AGC plant with parametric uncertainties are discussed. Gogoi and others have extensively worked on it and given excellent presentation on this topic with MATLAB software [6]. Additive uncertainty modelling is used to obtain the entire uncertainty set. The H_∞ controller design methodology is used to determine if the uncertain plant remains stable for the entire uncertainty set. The frequency domain application of this design method reduces the complexities of plant modelling. This controller design method has been applied to a single area non-reheat steam generator unit with parametric uncertainties. PI controller gains are obtained for the single area non-reheat steam generation AGC unit to satisfy a robust stability constraint and closed-loop stability. AGC influences the optimization of generator output, tie-line power interchange, customer billing, reducing Area Control Error (ACE), and the stability of a power operation system [4-8]. In [10], the authors described a method to reduce the mean value magnitude of the ACE below some threshold. A summary of the characteristics of a power generation system with AGC is presented in [8-9]. In [10], a PI controller was designed for AGC of a two-area reheat thermal system where a new ACE formulation is presented. A genetic algorithm (GA) method was used in [11] to optimize PI controller gains for a single area power system with multi-source power generation. In [12], a hybrid neuro-fuzzy controller was designed for AGC of two interconnected power systems. In [13], the authors designed an H_∞ robust controller for single-input multiple-output (SIMO) non-linear hydro-turbine generation model. The goal of their paper was to stabilize the system in presence of uncertainties in the turbine-governor-load model.

II. ROBUST STABILITY CONCEPT

Robust control is that branch of control systems engineering that explicitly deals with uncertainty in its approach to controller design. Robust control methods aim at achieving robust stability performance in the presence of uncertainties [14].

Loop shaping technique is an important classical controller design method [14]. During the 1980’s the classical feedback control methods were extended to a more formal method based on shaping closed-loop transfer functions such as the weighted sensitivity function. These developments led to a more deep understanding of robust control concepts. Extensive research during this time paved the way for modern robust control concepts and its application to real-world systems [14].

A control system is robust if it is insensitive to differences between the actual system and the model of the system that was used to design the controller. These differences are referred to as model/plant mismatch or simply model uncertainty. Furthermore, as mentioned in [14], the key idea of robust control is to check whether the design specifications are met for the “worst-case” uncertainty. The authors of [14] have taken the following approach to check robustness.

1. Check nominal system stability.
2. Determine the uncertainty set: Find a mathematical representation of the model uncertainty.
3. Check Robust Stability (RS): Determine whether the system remains stable for all plants in the uncertainty set.
4. Check Robust Performance (RP): If RS is satisfied; determine whether the performance specifications are met for all plants in the uncertainty set.

Figure 1, represents a general block diagram representation of a one degree-of-freedom feedback control system [9]. Here, *r* is the reference input, *u* is the control input to the plant, *y* is the actual plant output and *d* and *n* are the disturbance and noise signals respectively. G, G_d, and K are the plant model, disturbance model and controller respectively.

The objective of a control system is to make the output *y* behave in a desired way by manipulating *u* such that the control error remains small in spite of the disturbance present. The system output can be denoted as [9],

$$y = G(s)u + G_d(s)d \qquad (1)$$

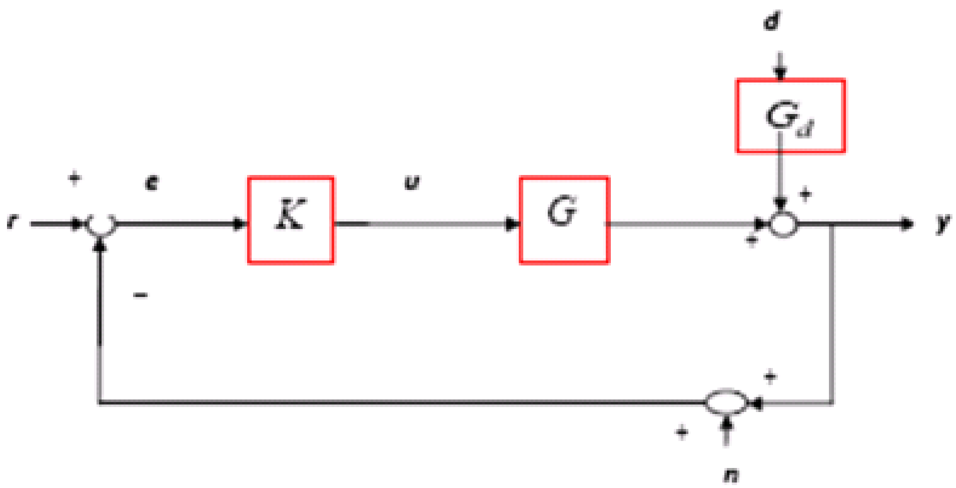

Figure 1. One degree-of-freedom feedback control system [9].

III. A SINGLE AREA NON-REHEAT STEAM GENERATION AGC UNIT CONTROLLER DESIGN BASED ON PI PARAMETERS

The high cost involved in the entire power system operation process demands a robust and stable control system that will ensure the smooth operation of power flow from the generating stations to the consumers. The interconnected grid system which allows power to be transferred from one control area to another is extremely complicated. The grid-system breakdown that occurred in 1965 on the east coast of North America, when an automatic control device that regulates and directs current flow failed in Queenstown, Ontario, caused a circuit breaker to remain open, is a perfect example of the vulnerability of this system. Therefore, a robust control structure to minimize these situations is of high priority [6].

Frequent load and generation mismatch tends to drive the system frequency from its nominal value. In [15], the author has mentioned how in real LFC systems, PI controllers play a major role. However, the lack of a satisfactory method for tuning the PI controller parameters leads to an inability to obtain good performance for various operating conditions and frequent load changes in a multi-area power system. The presence of uncertainties like system restructuring and changes in dynamic/load and operating conditions has led to an uncertainties being a serious issue in power system operation. All these factors reflect the necessity of a controller design method that will do a better job of tuning the controllers involved and that will robustly stabilize the control areas.

Our graphical design method is implemented to obtain all PI controller gains that will robustly stabilize a single-area non-reheat steam generator unit. For simulation purpose, we have assumed ±20% parametric uncertainty present in the governor and rotating mass and load model.

DESIGN GOAL

Our goal is to determine the range of PI controllers that will guarantee that the robust stability constraint

$$\| W_A(j\omega)K(j\omega)S(j\omega) \|_\infty \leq 1 \tag{2}$$

is satisfied where $W_A(j\omega)$, $K(j\omega)$ and $S(j\omega)$ are the additive uncertainty weight.

If above equation is satisfied then it can be confirmed that the selected controllers are capable of robustly stabilizing the perturbed system.

PLANT MODEL

A general block diagram of a non-reheat steam generator unit is shown in Figure 2. In this figure, $G_1(s)$, $G_2(s)$ and $G_3(s)$ represent the transfer function models of the primary speed governor, non-reheat steam turbine, and rotating mass and load models, respectively. B_i and R_i are the frequency bias factor and speed-droop characteristics for control area i. T_{ai} and T_{pi} are the total tie-line power interchange for control area i and tie-line power interchange between external control areas.

The PI controller is represented as K(s) where the input to the controller is the Area Control Error (ACE). ΔP_{L_i} is the load change experienced by control area i. ΔP_{c_i}, ΔP_{e_i}, ΔP_{g_i} and ΔP_{m_i} are the supplementary control output, governor input, primary governor output change, and turbine output power change. ΔP_{mech} and Δf_i are the mechanical power input to the rotating mass and load unit and frequency deviation from nominal value, respectively. $\frac{2\pi}{s}$ is the integral gain added to the feedback loop.

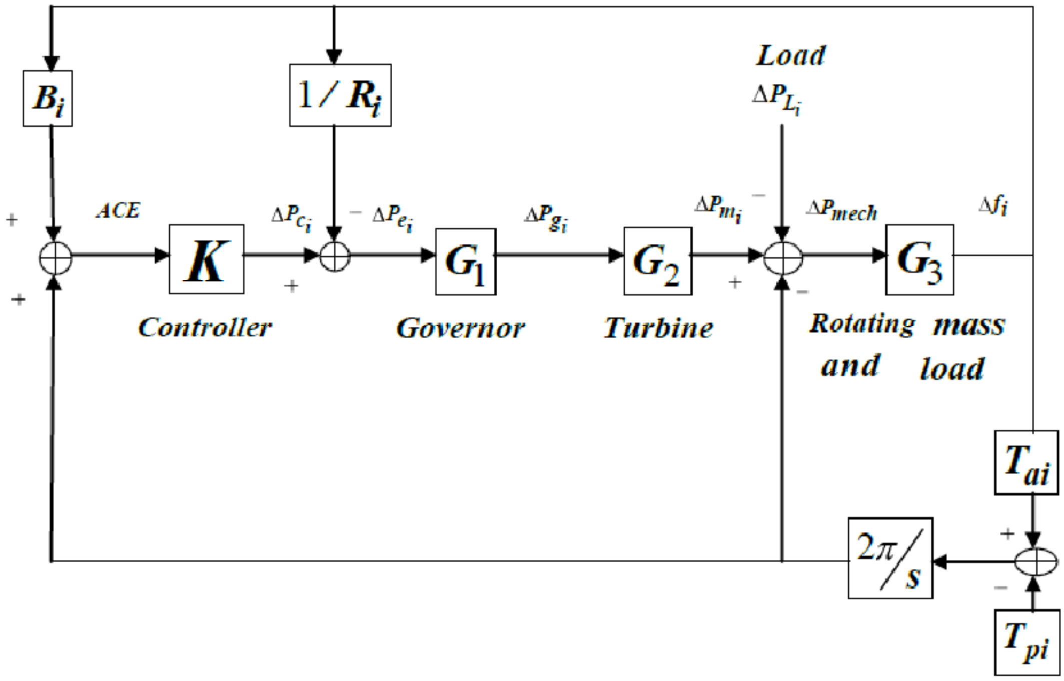

Figure 2. Block diagram of a single area non-reheat steam generation unit [9].

A general transfer function model of the speed governor is

$$G_1(s) = \frac{1}{1+sT_{gi}} \tag{3}$$

T_{gi} is the governor time coefficient. A general transfer function model of the non-reheat steam turbine is given by

$$G_2(s) = \frac{1}{1+sT_{ti}} \tag{4}$$

Where T_{ti} is the turbine charging time. A general transfer function model for the rotating mass and load model is

$$G_3(s) = \frac{1}{D_i+M_i s} \tag{5}$$

D_i and M_i are the load damping and the generator inertia coefficients, respectively. The tie line coefficients are

$$T_{ai} = \sum_{\substack{j=1 \\ j\neq i}}^{N} T_{ij} \tag{6}$$

$$T_{ai} = \sum_{\substack{j=1 \\ j\neq i}}^{N} T_{ij}\,\Delta f_j \tag{7}$$

Here T_{ij} is the tie-line synchronizing coefficient of area i with interconnected areas j and Δ_{f_j} is the corresponding frequency deviation in area j, respectively [8-9].

Frequency bias factor (B_i) for control area i is given as,

$$B_i = \frac{1}{R_i} + D_i \tag{8}$$

Figure 3, represents the nominal model $G_p(s)$, of this single area non-reheat generation unit. The closed loop transfer function for this model can be found from the following equations,

$$G_p(s) = G_{p1}(s) + G_{p2} \tag{9}$$

Where

$$G_{p1}(s) = \frac{2\pi}{s} T_{ai} G_3(s) G_2(s) G_1(s) \left[\left(1 + \frac{2\pi}{s} G_3(s) T_{ai}\right)^{-1} + \left(1 + \frac{1}{R_i} G_3(s) G_2(s) G_1(s)\right)^{-1}\right] \tag{10}$$

$$G_{p2}(s) = B_i G_3(s) G_2(s) G_1(s) \left[\left(1 + \frac{2\pi}{s} G_3(s) T_{ai}\right)^{-1} + \left(1 + \frac{1}{R_i} G_3(s) G_2(s) G_1(s)\right)^{-1}\right] \tag{11}$$

Substituting equation (10) and equation (11) into equation (9), we obtain the nominal model as,

$$G_p(s) = \left(\frac{2\pi}{s} T_{ai} + B_i\right) G_3(s) G_2(s) G_1(s) \left[\left(1 + \frac{2\pi}{s} G_3(s) T_{ai}\right)^{-1} + \left(1 + \frac{1}{R_i} G_3(s) G_2(s) G_1(s)\right)^{-1}\right] \tag{12}$$

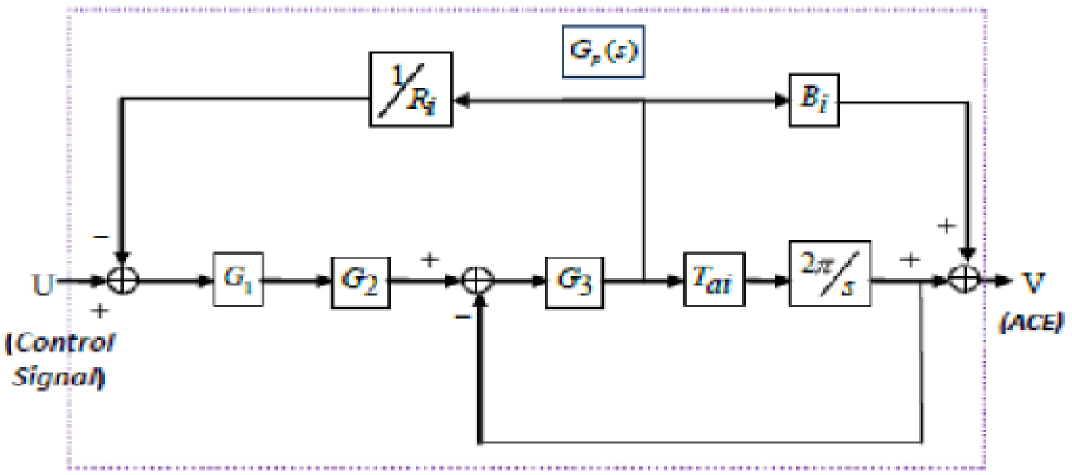

Figure 3. Nominal model of a non-reheat steam generator unit

ADDITIVE UNCERTAINTY WEIGHT DESIGN

The boundary for P $(\omega, \theta_A, \gamma) = 0$ for the (K_p, K_i) plane for $K_d = 0$ generates a PI controller as,

$$K(j\omega) = K_P + \frac{K_i}{j\omega} \tag{13}$$

In order to analyze robust stability for our designed controller we have assumed ±20% uncertainty in the plant parameters. This is shown in Table.

TABLE 1 UNCERTAINTY PARAMETERS

S.No	Plant Parameter	Uncertainty Range
1.	Governor Time Coefficient, T_{gl}	[0.053, 0.093]
2.	Load Damping Coefficient, D_l	[0.011, 0.016]
3.	Rotor Inertia Coefficient, M_l	[0.123, 0.189]

The nominal plant parameters for the single unit non-reheat generator unit are taken arbitrarily. In [9] these parameters (not exact one) were used to obtain the dynamic response of a closed loop steam generation unit for a step load disturbance of 0.02 per unit. The nominal parameter values are as shown in Table 3. In this paper, the results obtained by using these parameters were satisfactory as the robust stability constraint was satisfied.

TABLE 2 NOMINAL PLANT PARAMETERS

S.No	Plant Parameter	Value	Per Unit Measure
1	$D_1\left(=\frac{\Delta P_l}{\Delta\omega}\right)$	0.013	pu/Hz
2	$M_1 = \omega I$	0.1345	pu s
3	$R_1\left(=\frac{\Delta\omega}{\Delta P}\right)$	3.12	Hz/pu
4	T_{g1}	0.07	s
5	T_{t1}	0.40	s
6	T_{a1}	0.45	pu/Hz
7	$B_1\left(=\frac{1}{R_1}+D_1\right)$	0.3483	pu/Hz

The additive weight transfer function is selected as,

$$|W_A(j\omega)| \geq |G_\Delta(j\omega) - G_P(j\omega)| \tag{14}$$

Where $G_\Delta(s)$ represents the uncertain plant and $G_\Delta(j\omega) - G_P(j\omega)$ is the peak magnitude of the worst case uncertain plant such that

$$G_\Delta = \left(\left(\frac{2\pi}{s}T_{a1} + B_1\right) * G_{31} * G_2 * G_{11} * (Go1 + Go)\right) \tag{15}$$

Where *Go1* represent the feedback loop which includes $\frac{2\pi}{s}$ andT_{a1}, *Go* represent the feedback loop which includes $\frac{1}{R_1}$. G_{31} represents the worst case uncertainty rotating mass-load model, G_{11} represents the worst case uncertainty governor model.

IV. SIMULATION RESULTS

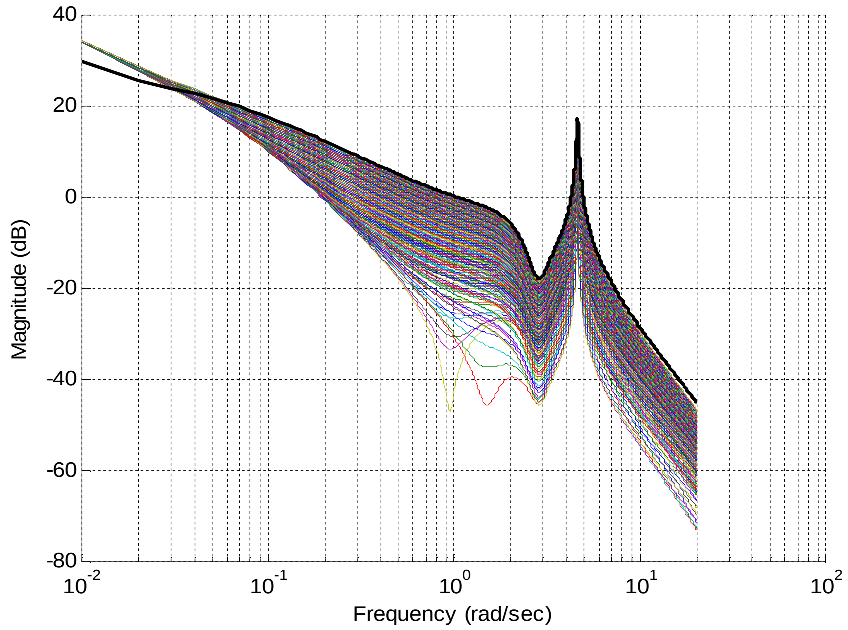

Figure 4. Additive weight representation

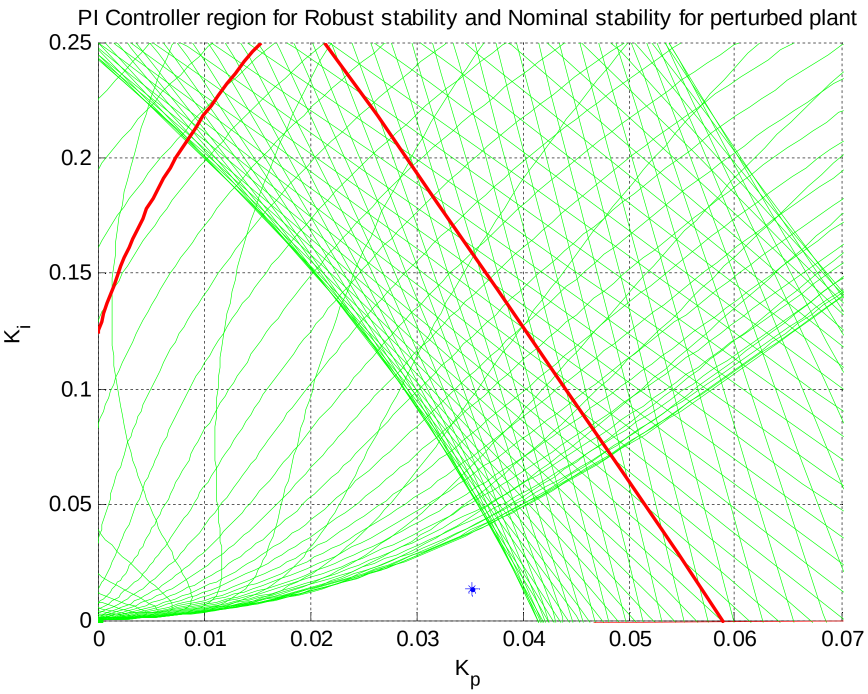

Figure 5. Nominal stability boundary and robust stability region for K_p and Ki values

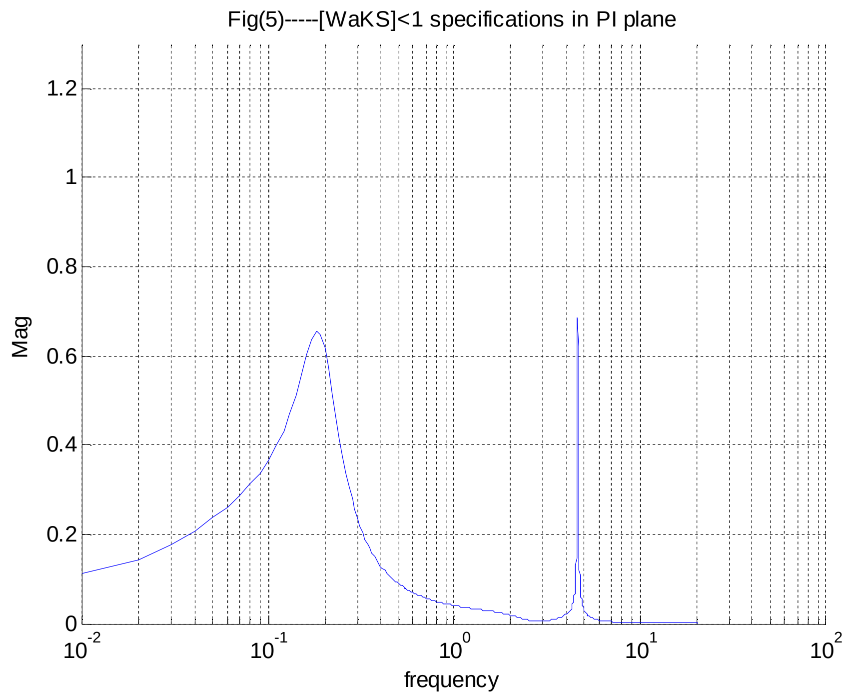

Figure 6. Magnitude of $W_A(j\omega)K(j\omega)S(j\omega)$ <1 for a point inside the robust stability region (Stable)

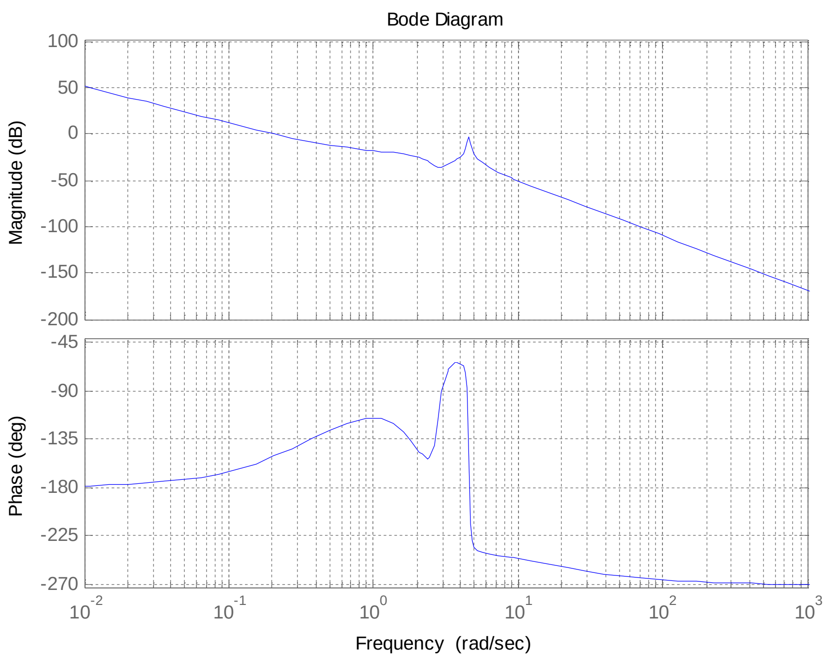

Figure 7. Bode plot showing stable operation

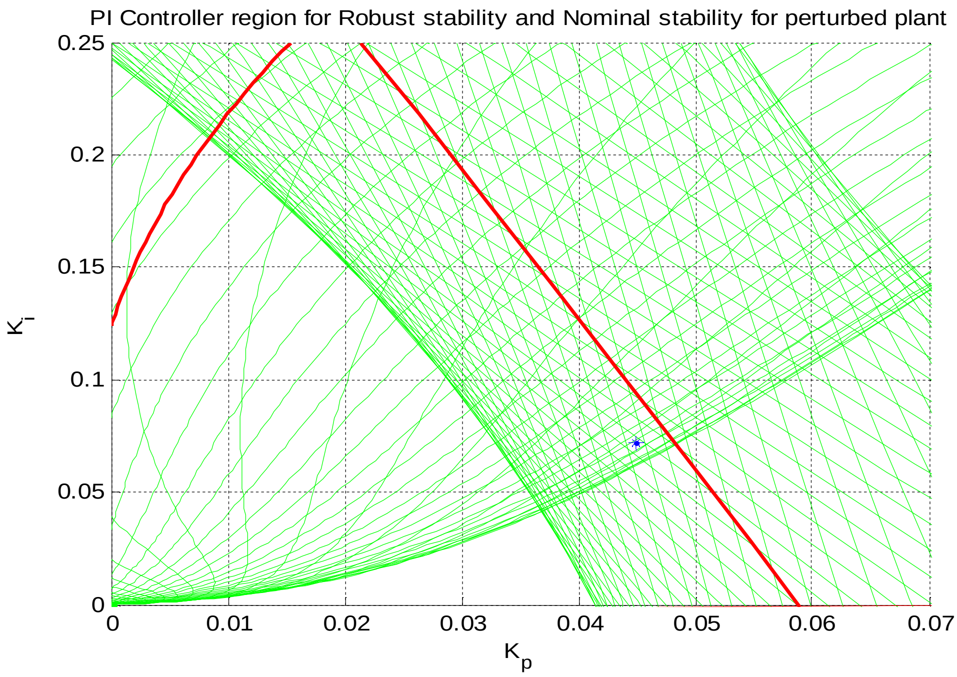

Figure 8. Nominal stability boundary and robust stability region for K_p and Ki values

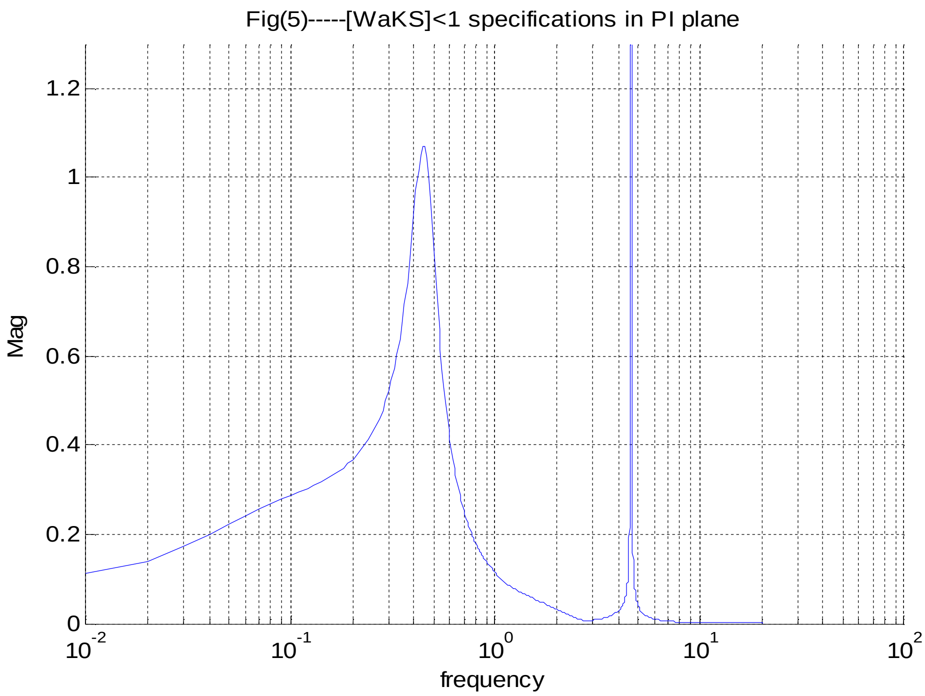

Figure 9. Magnitude of $W_A(j\omega)K(j\omega)S(j\omega)$ >1 for a point outside the robust stability region (Unstable)

V. CONCLUSION

The graphical design method for obtaining all PI controllers that satisfied a robust stability constraint for a non-reheat steam generator AGC unit is discussed. In this paper, we have used additive uncertainty modelling technique to obtain an additive weight that bounds the entire uncertainty set. It is concluded from simulation results that the value of (K_P and K_I gain) of PI controllers within robust stability region is always stable. Gain outside of robust stability region but within nominal stability region need not necessarily be always stable.

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