Appropriate Generation Rate Constraint (GRC) Modeling Method for Reheat Thermal Units to Obtain Optimal Load Frequency Controller (LFC)

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***Abstract*—This paper focuses on choosing a suitable dynamic model for simulation of generation rate constraint (GRC) for load frequency control (LFC) of an interconnected realistic reheat thermal-thermal power system. Two different dynamic models for simulation of the GRC are investigated in details which are named as open loop and closed loop GRC models. These models have been used widely in literature interchangeably without any further description to the reason of selected modeling method and its suitability. This paper makes an attempt to help in choosing more effective and appropriate GRC structure pertained to reheat thermal units based on dynamic simulations to obtain optimal LFC. Reheat thermal units are examined with different GRC models. Then, integral of time multiplied squared error (ITSE) performance index is minimized by an improved particle swarm optimization (IPSO) algorithm to optimize proportional-integral-derivative (PID) controller parameters. All simulations are performed in MATLAB/ SIMULINK environment. The results of eigenvalue analysis, dynamic simulations, and robustness analysis reveal the appropriate GRC modeling method for thermal units to attain high-performance and optimal LFC design.**

***Keywords*—GRC non-linearity; reheat thermal unit; open loop modelling, closed loop modelling; ITSE, IPSO; dynamic simulation**

I. INTRODUCTION

Load frequency control (LFC) is an important function in frequency regulation of modern power Systems. In order to get a precise realization and accurate insight of the LFC issue, it is essential to take into account the important constraints and main inherent requirements such as physical constraints which affect the power system dynamics. Generation rate constraint (GRC) is a physical constraint that means practical limit on the rate of the change in the generating power due to physical limitations of turbine. GRC has major influence on realistic power system performance due to its non-linearity characteristic. In practice, the rate of active power change that can be attainable by thermal units has a maximum limit [1]. So, the designed LFC for the unconstrained generation rate situation may not be suitable and realistic. The main reason to consider GRC is that the rapid power increase would draw out excessive steam from the boiler system to cause steam condensation due to adiabatic expansion. Since the temperature and pressure in the high pressure (HP) turbine are normally very high with some margin, it is expected that the steam condensation would not occur with about 20% steam flow change unless the boiler steam pressure itself does not drop below a certain level [2]. Thus, it is possible to increase generation power up to about 1.2 pu of normal power during the first tens of seconds. After the generation power has reached this marginal upper bound, the power increase of the turbine should be restricted by the GRC. Since the GRC has significant impact on the dynamic response of the power system LFC, effective inclusion of this constraint in a real frequency control scheme will greatly improve control performance [3]. The power system may face large momentary disturbance if GRC is not considered in the controller design [4].

After a load disturbance in a power system, area control error (ACE) signals and control signals deviate from zero. The required power to compensate frequency deviations is provided through a specific ramp rate. The required power to maintain the system in normal condition is prepared by limit rate due to the GRC. The effect of the GRC will be more noticeable when the system encounters with greater step load perturbation (SLP) [5]. In this way, the system attempts to provide greater power in a fast time horizon to ensure integrity of the interconnected system, but the GRC limits the response of the generating units by reducing the rate of increasing required power to reject the disturbances. The negative effect of GRC becomes more important when it combines with the speed governor dead-band (GDB), and hence the system frequency may not regain its nominal value in a specified time (determined by relays setting time) and hence the protective devices and relays react. Therefore, the system falls into the unstable condition [5]. A literature review shows that in the simultaneous presence of important system constraints and nonlinearities like GDB and GRC, the dynamic responses of the system experience larger overshoots and longer settling times of frequency and tie-line power oscillations, compared to the case of without considering GRC and GDB [6, 7]. The GDB and GRC limit the immediate response of the power system to reject disturbances. Thus, this limitation must be considered to avoid instability in the realistic multi-area power systems. In the presence of GRC and GDB, the system becomes highly nonlinear (even for small load perturbation) and hence in a real power system, the performance of the designed controller is significantly degraded [5].

Over the years till now, two main methods have been developed to consider the GRC for the analysis of frequency control systems. In [8], a three-area thermal system under deregulated environment is considered with GRC which is modeled as “open loop” method; a name that we use hereafter for one of two methods employed in papers for modeling of GRC. In [9], automatic generation control (AGC) of a multi-area hydrothermal system with GRC modeled in open loop method are investigated. In [5], a three-area reheat thermal units are examined taking into account GDB and GRC nonlinearities in which the GRC is modeled in open loop method. GRCs of both hydro and thermal units are modeled by the open loop method. In [10], GRCs of an interconnected hydrothermal system are simulated by the open loop model.

In [11], a nonlinear thermal turbine model with GRC is utilized which we name as the “closed loop” GRC model. In order to take effect of the GRC in the simulations, most of papers replace linear model of thermal turbine with a nonlinear closed loop model [2, 12, 13]. In [7], LFC of interconnected reheat thermal power system considering GDB and GRC nonlinearities is investigated in which the GRC is simulated by the closed loop model. The authors in [14], adopt an anti-GRC structure to overcome the negative effects of GRC on frequency stability where the GRC of the thermal unit is simulated by closed loop model. In [15], GRC is taken into theoretical consideration in the LFC design procedure. In doing so, nonlinear turbine model is used in which the closed loop model of GRC is applied in simulations to emulate the practical limit on the response of the turbine. In [16], GDB and GRC nonlinearities are taken into account simultaneously for a two-area reheat thermal units.

Above literature survey reveals that investigation on an appropriate GRC modeling method for LFC can be a major concern. In this paper, appropriate GRC modeling for reheat thermal plants of a two-area realistic interconnected power system is investigated by dynamic simulations. Proportional-integral-differential (PID) controller is adjusted by an improved particle swarm optimization (IPSO) algorithm in presence of the GDB and GRC physical constraints because ignoring these lead to nonrealistic results.

II. POWER SYSTEM STUDIES

A. Realistic interconnected power system

Fig. 1 shows the transfer function model of interconnected reheat thermal system including GDB and GRC constraints. The block descriptions of reheat thermal plants are shown on Fig. 1. The system parameters are given in TABLE I. The GRC of thermal units can be modeled in either closed loop or open loop method. Here, the value of GRC for reheat thermal units is considered as 10%/min, i.e.:

$$\left|\Delta\dot{P}_{th}\right| = 0.1\left({}^{pu}\!/\!_{min}\right) = 0.0017\left({}^{pu}\!/\!_{sec}\right) \tag{1}$$

Hence, The GRC for the units can be taken into account by adding two limiters , bounded by ±0.0017 within the turbines in the closed loop or open loop method as shown in Fig. 2 to restrict the generation ramp rate for the thermal plants [6, 17].

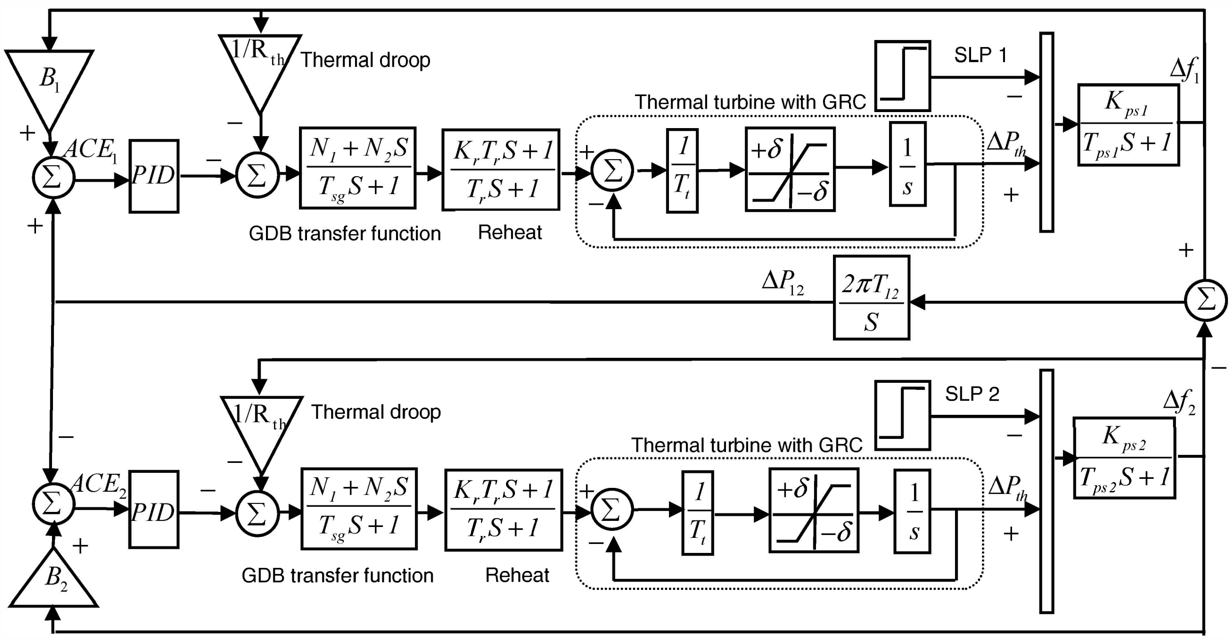
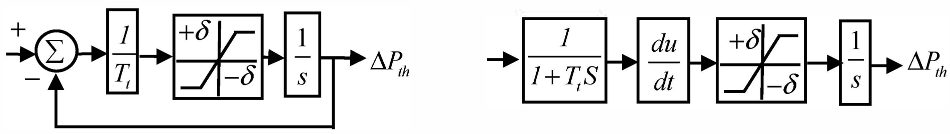


Fig. 1. Transfer function model of interconnected thermal power system considering GDB and GRC in closed loop model



(a)

(b)

Fig. 2. GRC models: (a) Closed loop modeling (b) Open loop modeling

The GDB is defined as the total magnitude of a sustained speed change within which there is no change in valve position of the turbine. The GDB of the 0.06% backlash type can be linearized in terms of change and the rate of change in the speed. In this paper, following most recent paper [18], N_1 and N_2 in the GDB transfer function model are N_1=0.8 and N_2=-0.2/π, respectively. Droop of thermal units is set at 4%.

TABLE I. PARAMETERS OF THE INTERCONNECTED POWER SYSTEM

Parameter	Value	Description
f	50 Hz	System frequency
R_{th}	2	Speed regulation parameter (Hz/puMW)
T_{sg}	0.06 sec	Governor time constant of steam turbine
T_t	0.3 sec	Steam turbine time constant
K_r	0.3	Steam turbine reheat constant
T_r	10.2 sec	Steam turbine reheat time constant
T_{ps1}, T_{ps2}	11.49 sec	Power system time constants
K_{ps1}, K_{ps2}	68.9655	Power system gains (Hz/puMW)
T_{12}	0.0433	Synchronizing coefficient
B_1, B_2	0.4312	Frequency bias coefficients
$\pm\delta$	±0.0005	Positive and negative ramp rates
Δf_1, Δf_2		Area frequency deviations
ΔP_{12}		Tie-line power deviation
N_1=0.8, N_2=-0.2/π		Fourier coefficients of GDB transfer function

B. *Objective function for controller design*

In order to damp effectively the oscillations, considering a suitable objective function is very important to find the controller parameters. In this work, the integral of time multiplied squared error (ITSE) performance index is considered as the objective function as following:

$$ITSE = \int_0^{Tsim} t\left[\Delta f_1^2 + \Delta f_2^2 + \Delta P_{12}^2\right]dt \qquad (2)$$

where T_{sim} denotes the simulation time. The ITSE index uses advantages of both integral of squared error (ISE) and integral of time multiplied absolute error (ITAE) indices, as it utilizes squared error and time multiplication to weight large oscillations and penalize long settling time. The ITSE performance index has been employed recently in [18, 19] to design AGC of interconnected power systems. In order to design LFC, an optimization problem is solved by improved particle swarm optimization (IPSO) algorithm to minimize the ITSE index to obtain the optimal parameters of the PID controllers, subject to following constraints:

$$0 \le K_{P1}, K_{I1}, K_{D1}, K_{P2}, K_{I2}, K_{D2} \le 5 \qquad (3)$$

C. *Improved particle swarm optimization (IPSO) algorithm*

Particle swarm optimization (PSO) is a member of wide category of swarm intelligence-based optimization algorithms. PSO is one of most well-known heuristic evolutionary algorithms that has found many applications in solving of engineering optimization problems. In the case of populations with large diversity, improved PSO (IPSO) algorithm recently introduced in [20], employs crossover operator so that the search space can be successfully surveyed. This helps in finding the global optimal solution more precisely. The IPSO is employed here to minimize the proposed objective functions due to its great effectiveness in optimizing of the parameters. To find optimal parameters of the PID controller, IPSO should explore in three-dimensional search space. To start optimization process, initially some executions have been performed with different values of the IPSO parameters to assess if IPSO will find satisfactory results or not. The parameters of IPSO algorithm should be selected carefully to provide high performance. The parameters of our written MATLAB-based IPSO program are selected as: n=30; m=3; ω_{min}=0.4; ω_{max}=0.9; c_1=c_2=2; γ=0.1; t_{max} =30; CR=0.6, where n is the population size; m is total number of parameters to be optimized; ω_{max}, ω_{min} are the initial and final inertia weights; c_1, c_2 are acceleration coefficients; γ is a chosen number in interval (0, 1) to control the maximum velocity vector; t_{max} is total number of the iterations; and CR is crossover rate.

III. SIMULATION RESULTS AND DISCUSSES

A. *Simulation of reheat thermal power system considering open loop and closed loop models of GRC*

In this case, the time domain simulations are realized for 0.01pu SLP in area 1 applying GRC in the open loop model. The proposed IPSO algorithm is repeated many times to solve the optimization problem. Some near optimal solutions for nominal system parameters obtained after numerous runs are shown in TABLE II. The solution with minimum value of the ITSE index is chosen as final optimized parameters of the controller which is highlighted in TABLE II. It is noteworthy to say that the running time of the IPSO algorithm with application of the open loop GRC model is very longer than the simulation time for the closed loop GRC model. The damping measures such as settling time (T_S) with 5% criterion, system oscillatory modes and damping ratios (ζ) corresponding to the open loop and closed loop models of the GRCs are presented in TABLE III. These damping indices are very important in evaluating the LFC dynamic performance. Fig. 3 shows the frequencies and tie-line power oscillation responses.

TABLE II. SOME NEAR OPTIMAL PID CONTROLLERS IN DIFFERENT GRC MODELING METHODS

	K_{P1}	K_{I1}	K_{D1}	K_{P2}	K_{I2}	K_{D2}	ITSE
Open loop	3.5517	2.1053	2.6671	1.5975	1.0933	0.2780	0.0936
	4.2658	0.9839	2.0164	5.0000	2.8834	2.0512	0.0947
	4.4303	0.6949	0.0925	1.7326	2.1834	2.1972	0.0789
	2.4579	0.7529	0.9707	2.7274	2.1482	0.9876	0.0832
Closed loop	0.1146	0.0766	2.8878	2.0251	0.1745	2.2962	0.0734
	0.0902	0.0618	3.0861	2.7809	0.1062	2.5285	0.0763
	0.0837	0.0691	2.0957	1.1408	0.2644	0.9304	0.0795
	0.5334	0.0563	3.3569	1.9686	0.3821	1.4893	0.1212

TABLE III. SYSTEM DAMPING CHARACTERISTICS WITH OPEN LOOP AND CLOSED LOOP MODELS OF GRC

	oscillatory mode	ζ	Signal	T_S
Open loop			Δf_1	>50
	-0.0435 ± 1.8063i	0.0241	Δf_2	>50
			ΔP_{12}	>50
Closed loop	-0.2418 ±2.5228i	0.0954	Δf_1	27.7025
	-1.0492 ±1.2064i	0.6562	Δf_2	29.8534
	-0.0728 ±0.0422i	0.8654	ΔP_{12}	30.9709

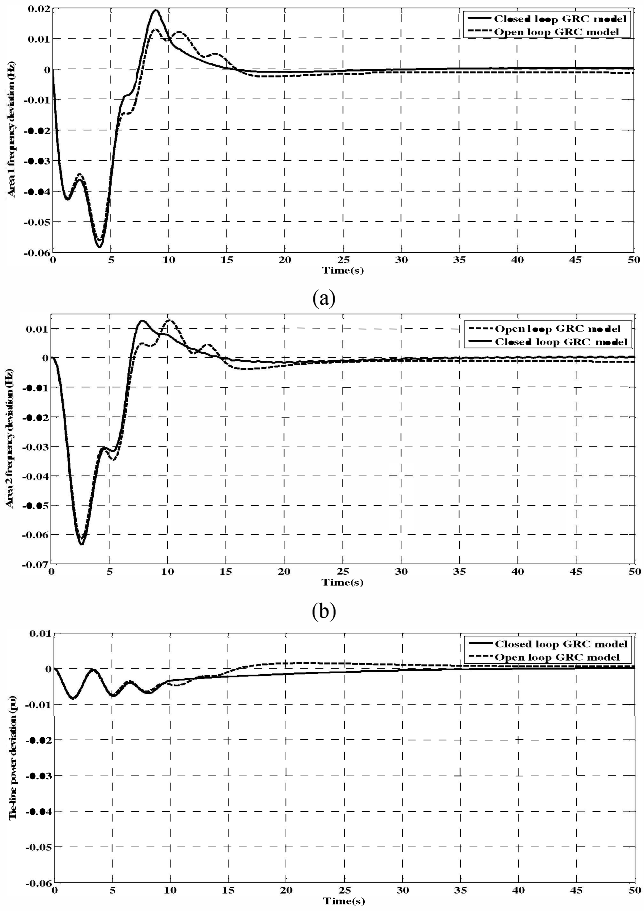


Fig. 3. Dynamic responses: (a) Δf_1, (b) Δf_2, and (c) ΔP_{12}

It is clear from TABLE III that the T_s in closed loop model is significantly smaller than that of obtained from the open loop modeling method. Also, the minimum damping ratios of the system with closed loop GRC is very larger than the open loop counterpart. It can be seen from Fig. 3 that with the open loop GRC model, the area frequencies and the tie-line power deviations regulate to zero with difficulty. As it is obvious, even with the optimized PIDs, the oscillations persist for a long time and a small steady state error remains considering the open loop GRC model. I. e., the LFC system can no longer suppress the oscillations to drive back them to zero, effectively. With application of the closed loop GRC model, the area frequencies and tie-line power oscillations are damped to zero fully.

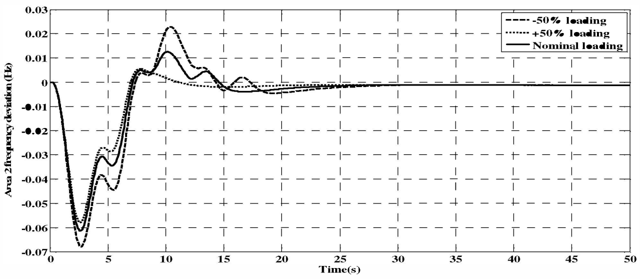
B. Robustness analysis against uncertainties in system loading condition and parameters

The sensitivity analysis is carried out to investigate the robustness of the GRC models to wide variations in the system loading condition and parameters. The loading condition, steam turbine time constant T_t, and the synchronizing torque T_{12} are varied in the range of ±50% from nominal values, individually. The simulation results with these conditions for 0.01pu SLP in area 1 are summarized in TABLE IV. It can be observed that even with consideration of ±50% uncertainty in loading condition, T_t, or T_{12}, the ITSE index and minimum damping ratios of the system with closed loop GRC model are better than the other. Increase (or decrease) of ITSE index can be interpreted as decrease (or increase) of system damping performance. The damping ratios with closed loop GRC are larger than with the open loop GRC. Also, the T_S of the area frequencies and tie-line power responses with closed loop GRC model are smaller than open loop model, considerably.

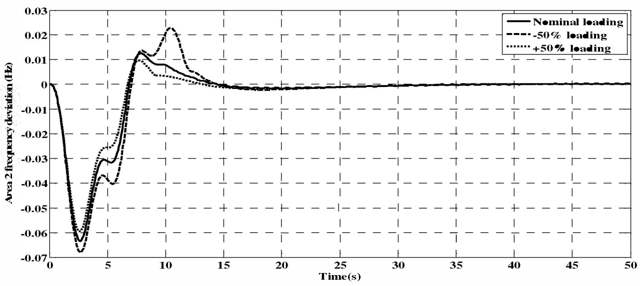
TABLE IV. ROBUST ANALYSIS OF GRC MODELS AGAINST VARIOUS UNCERTAINTY SCENARIOS

% change	GRC model	oscillatory Modes	ζ	ITSE	signal	T_S
+50% in loading	open loop	-0.0652 ± 1.8057i	0.0361	0.0573	Δf_1 Δf_2 ΔP_{12}	>50 >50 >50
	Closed loop	-0.2725 ± 2.5347i	0.1069		Δf_1	28.5075
		-1.0704 ± 1.2459i	0.6516	0.0564	Δf_2	29.9483
		-0.0727 ± 0.0423i	0.8645		ΔP_{12}	30.6714
-50% in loading	Open loop	-0.0217 ± 1.8067i	0.0120	0.1243	Δf_1 Δf_2 ΔP_{12}	>50 >50 >50
	Closed loop	-0.2113 ± 2.5111i	0.0838		Δf_1	27.3392
		-1.0265 ± 1.1640i	0.6614	0.1150	Δf_2	29.4890
		-0.0730 ± 0.0421i	0.8664		ΔP_{12}	30.9290
+50% in T_t	open loop	-0.0435 ± 1.8063i	0.0241	0.0789	Δf_1 Δf_2 ΔP_{12}	>50 >50 >50
	Closed loop	-0.0774 ± 2.3969i	0.0323		Δf_1	26.9940
		-0.7345 ± 1.1700i	0.5317	0.0743	Δf_2	29.9638
		-0.0728 ± 0.0427i	0.8625		ΔP_{12}	31.0314
-50% in T_t	open loop	-0.0435 ± 1.8063i	0.0241	0.0789	Δf_1 Δf_2 ΔP_{12}	>50 >50 >50
	Closed loop	-0.6367 ± 2.5181i	0.2451		Δf_1	28.4601
		-1.8126 ± 1.0041i	0.8748	0.0741	Δf_2	31.8648
		-0.0729 ± 0.0416i	0.8682		ΔP_{12}	31.0902
+50% in T_{12}	open loop	-0.0435 ± 2.2125i	0.0197	0.1015	Δf_1 Δf_2 ΔP_{12}	>50 >50 >50
	Closed loop	-0.0870 ± 2.8701i	0.0303		Δf_1	28.9176
		-1.1412 ± 1.2119i	0.6856	0.1058	Δf_2	30.1953
		-0.0738 ± 0.0424i	0.8667		ΔP_{12}	29.2244
-50% in T_{12}	open loop	-0.0435 ± 1.2769i	0.0340	0.0976	Δf_1 Δf_2 ΔP_{12}	>50 >50 >50
	Closed loop	-0.5698 ± 2.1238i	0.2591		Δf_1	27.1840
		-0.8101 ± 1.1409i	0.5789	0.0726	Δf_2	32.9511
		-0.0703 ± 0.0413i	0.8622		ΔP_{12}	32.9511

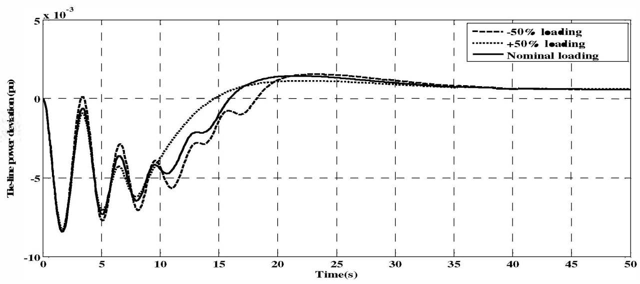
The dynamic responses considering aforementioned uncertainties are depicted in Figs. 4 - 6. One can infer from these figures that there is insignificant impact of the changes in the system loading condition and parameters on the obtained results with closed loop GRC, in that, the frequencies and tie-line power oscillations are suppressed as well. Moreover, by employing closed loop GRC model, the steady state error can be eliminated effectively. One important point is that as we know from the linear control theory, the negative-feedback closed loop system usually tends to increase the system stability rather than the open loop. Moreover, since the derivative operator is sensitive to discontinuity, the sudden changes in loads or system parameters of direct path (in open loop GRC model) can degrade the system performance significantly. Our robustness analysis reveals that the closed loop GRC model is quite robust. Hence, the parameters of optimal PID controllers once set for nominal condition need not to be reset for ±50% variations in the system parameters and loading condition from their nominal values.



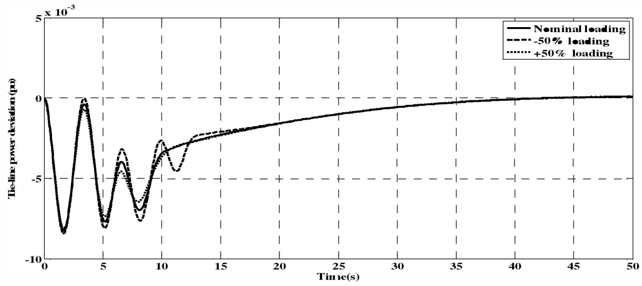
(a1) Δf_2 with open loop GRC model



(a2) Δf_2 with closed loop GRC model

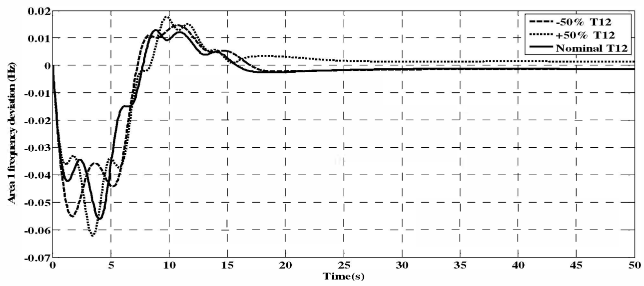


(b1) ΔP_{12} with open loop GRC model

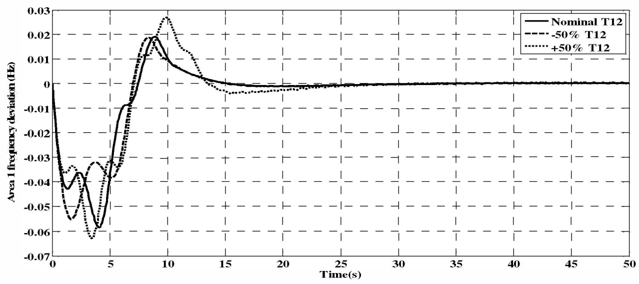


(b2) ΔP_{12} with closed loop GRC model

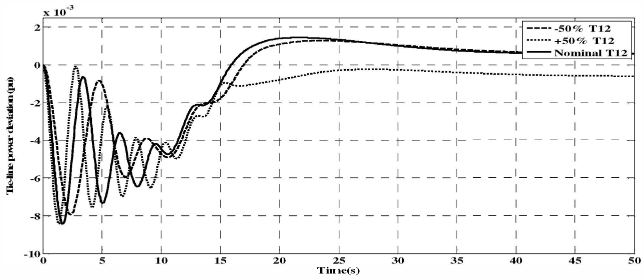
Fig. 4. Robustness analysis against uncertainty in loading condition



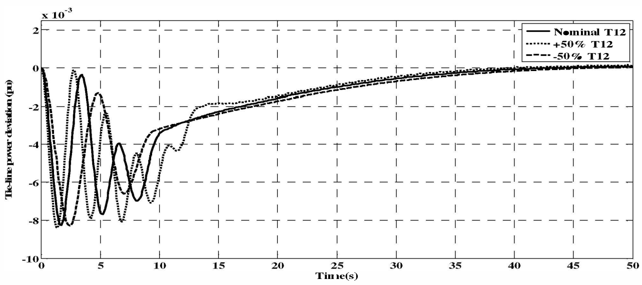
(a1) Δf_1 with open loop GRC model



(a2) Δf_1 with closed loop GRC model

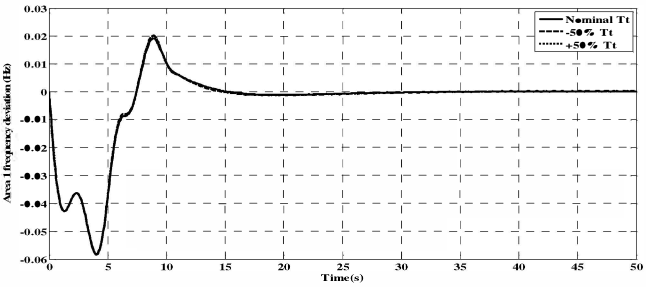


(b1) ΔP_{12} with open loop GRC model

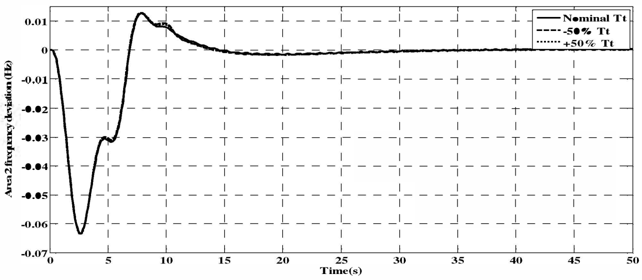


(b2) ΔP_{12} with closed loop GRC model

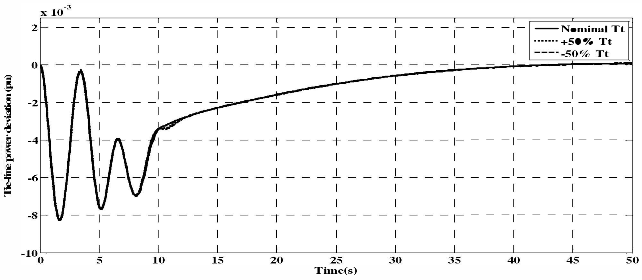
Fig. 5. Robustness analysis against uncertainty in T_{12}



(a) Δf_1 with closed loop GRC model



(b) Δf_2 with closed loop GRC model



(c) ΔP_{12} with closed loop GRC model

Fig. 6. Robustness analysis against uncertainty in T_t

IV. CONCLUSION

In this paper an effort has been made to choose the appropriate SIMULINK model of GRC in reheat thermal units using dynamic simulations to obtain optimal LFC. The dynamic performance of the interconnected thermal power system considering GRC and GDB nonlinearities has been evaluated by applying the open loop and closed loop models of the GRC, individually. The effectiveness of both models in damping of the area frequencies and tie-line power oscillations has been examined. The eigenvalue analysis and time domain dynamic simulation results show that with the closed loop model of GRC, greater dynamic performance can be attained. Also, the robustness of the power system equipped with the different GRC models has been investigated by sensitivity analyses considering uncertainty scenarios in system loading condition and parameters. These analyses exhibit that the optimized PID controllers are quite robust and performs satisfactorily under uncertainty conditions when the closed loop GRC model is applied. Hence, clearly this paper suggests the closed loop model of GRC for dynamic simulations of reheat thermal units in LFC studies.

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