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ROBUST DECENTRALIZED TURBINE-GOVERNOR CONTROL SUBJECT TO CONSTRAINT ON TURBINE OUTPUT

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Abstract: This paper considers the decentralized turbine-governor control design for the damping of low-frequency, inter-area oscillations in electric power systems. A time-varying model that explains oscillations caused by parametric resonance is employed to design a controller. A robust turbine-governor controller design is presented on the basis of the model. Furthermore, a basic idea for incorporating constraints on the amplitude of the turbine output is introduced. By using a two-machine-quasi-infinite-bus system, we demonstrate that the proposing control effectively damps low-frequency oscillation.

Keywords: Power system control, Power system oscillation, Robust control, Saturation of turbine output

1. INTRODUCTION

The electric power system is known as a large-scale, complex system that is composed of many electric devices and mechanical components. It is also known that the system frequently shows nonlinear phenomena. A sustained power oscillation is one of the nonlinear phenomena by which a rotor angle of each synchronous machine oscillates in frequencies that are different from its original electromechanical resonance frequencies. This is due to mutual effects among different machines. Moreover, the mechanical components including control devices such as a power system stabilizer, a static var compensator and a turbine-governor system have saturation nonlinearity. Hence, we must take it into account in control design.

This paper considers a robust controller design based on a nonlinear model that takes account of the mutual effects among machines and saturation nonlinearity as well. By using this model, we design a steam-valving controller of an electrical-hydraulic governor system. Although, controlling a conventional mechanical-hydraulic governor has little effect on the system stability, the electrical-hydraulic governor system is attracting attention in recent years as an effective device to damp the low-frequency inter-area oscillations (Rogers, 2000; Lu *et al.*, 2001). Hence, the main issue of the controller design is to consider saturation nonlinearity in the turbine output, on which a strict constraint is imposed to protect a steel shaft.

The controller design is based on a constructive way, where the backstepping technique (Krstić *et al.*, 1995; Khalil, 1996), which is an emerging new control design tool for nonlinear systems, is employed to consider designs for subsystems successively. In the first step, by taking account of saturation nonlinearity, we design a fictitious controller that produces an idealized mechanical input to a generator. In the following steps, we obtain the steam-valving controller that compensates the turbine and governor dynamics and produces the idealized mechanical input indirectly. By using a nonlinear simulation we verify that the proposed controller design is effective and can improve the control performances of the steam valving control system.

2. DERIVATION OF A NONLINEAR MODEL

2.1 *Behavior of power system*

To express the power oscillation, we use a swing equation of a synchronous machine that is connected to other machines. It is given by

$$M_i \frac{d^2\theta_i}{dt^2} + D_i \frac{d\theta_i}{dt} = P_{m_i} - \frac{E_i E_B}{X_{i0}} \sin\theta_i - \sum_{j=1, j\neq i}^{N} \frac{E_i E_j}{X_{ij}} \sin(\theta_i - \theta_j) \quad (1)$$

where $i = 1, \cdots, n$ and i stands for the ith machine (Guo *et al.*, 1999). Here, M_i, D_i and θ_i are the moment of inertia, the damping coefficient and the rotor angle relative to the phase angle of an infinite bus, which represents an external large network. The magnitude of the infinite-bus voltage E_B is assumed to be constant even when the ith machine is perturbed. P_{m_i} is the mechanical input to the ith machine. X_{ij} is an inductance of the transmission line between machines i and j, X_{i0} is an inductance of the transmission line between the machine i and the infinite bus, and E_i is the voltage of the ith machine bus. The swing equation describes the behavior of a rotor angle of a machine. The mutual relationships among machines are taken into account by the last term of the equation (1).

Conventionally, under the condition that E_j and θ_j are constant, the analysis of the power oscillation and the control design to stabilize the power system are considered by using a linearized model of the equation (1) (Kundur, 1994). This means that the analysis and the control design are performed under the assumption that the model of a machine is not influenced by transient behavior of other machines. However, once a steady state of the system breaks, representing a changed operating condition or a perturbed external network, E_j and θ_j vary accompanying transient responses.

Example 1
In order to see the influence of transient behavior of another machine on the ith machine, we observe the response of the ith rotor angle in respect of changes of $\theta_j(0)$ from a steady-state value θ_j^0 in a two-machine-infinite-bus system ($N = 2$), where a steady-state equation:

$$0 = P_{m_i}^0 - \frac{E_i E_B}{X_{i0}} \sin\theta_i^0 - \sum_{j=1, j\neq i}^{2} \frac{E_i E_j^0}{X_{ij}} \sin(\theta_1^0 - \theta_2^0) \quad (2)$$

holds. Here, $\left(P_{m_i}^0, \theta_j^0, E_j^0, \theta_j^0\right)$ represents a set of state-state variables of an equilibrium point. The system is depicted in Figure 1. Parameters that we used are listed in Table 1. The responses of θ_1 and θ_2 are plotted in Figures 2 and 3. In Figure 2 free responses of θ_1 and θ_2 from an initial value: $(\theta_1(0), \theta_2(0)) = (\theta_1^0 + 0.01, \theta_2^0)$ are plotted, in Figure 3 free responses from an initial value: $(\theta_1(0), \theta_2(0)) = (\theta_1^0, \theta_2^0 + 0.01)$ are plotted. It can be seen that an oscillation mode of a machine varies depending on the initial value. This shows that the dynamics of each machine is influenced by operating conditions of other machines.

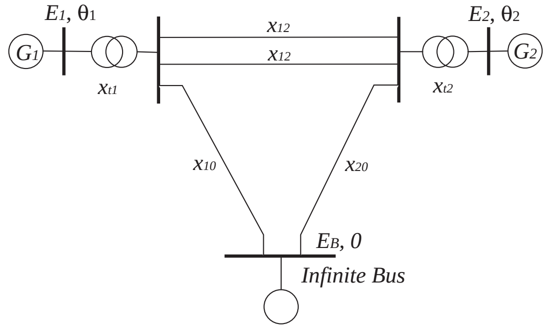

Fig. 1. Two-machine-infinite-bus system

Table 1. Parameters of machines and lines

	#1	#2
H_i [MWs/MVA]	2.0	6.0
D_i	0.0029	0.0029
x_{t_i} [p.u.]	0.129	0.11
E_i [p.u.]	1.0	1.0
P_{m_i} [p.u.]	1.1804	1.0842
x_{12} [p.u.]	x_{10} [p.u.]	x_{20} [p.u.]
0.55	0.53	0.6

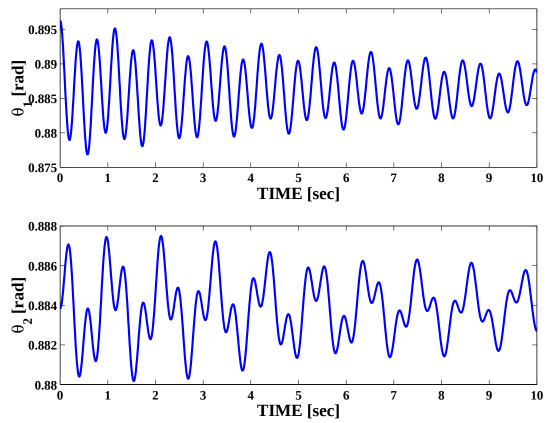

Fig. 2. Responses of phase angles with an initial condition: $\theta_1(0) = \theta_1^0 + 0.01, \theta_2(0) = \theta_2^0$

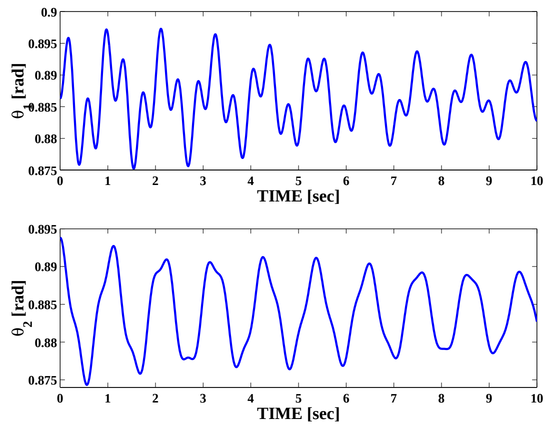

Fig. 3. Responses of phase angles with an initial condition: $\theta_1(0) = \theta_1^0, \theta_2(0) = \theta_2^0 + 0.01$

2.2 *Time varying model of the oscillation*

To capture the machine dynamics influenced by other machines, we assume that the voltages and rotor angles of other machines vary as

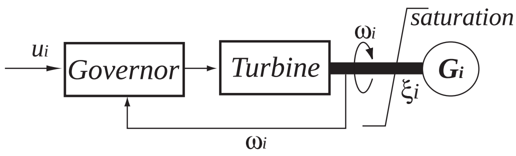

Fig. 4. Turbine & Governor System

Table 2. Constants of the turbine governor system

T_{T_1}	T_{T_2}	T_{G_1}	T_{G_2}
0.2	0.2	0.5	0.5

$$\Delta E_j := E_j - E_j^0 = E_j^1 e^{-\alpha t}\sin(\omega t + \phi_E)$$
$$\Delta\theta_j := \theta_j - \theta_j^0 = \theta_j^1 e^{-\alpha t}\sin(\omega t + \phi_\theta)$$

where $\alpha > 0,\ j = 1, 2, \cdots, N$ while E_B is a constant. Under the above assumption, by expanding the equation (1) about an operating condition into a series and neglecting high order terms after the third order component, we have

$$\Delta\ddot{\theta}_i + \frac{D_i}{M_i}\Delta\dot{\theta}_i + \frac{1}{M_i}\left(\sum_{j=0,j\neq i}^{N} K_{ij} + e^{-\alpha t}\sum_{j=1,j\neq i}^{N} K_{ij}F_{ij}\cos(\omega t + \phi_{F_{ij}})\right)\Delta\theta_i = \frac{1}{M_i}\left(\Delta P_{m_i} + e^{-\alpha t}\sum_{j=1,j\neq i}^{N} K_{ij}H_{ij}\cos(\omega t + \phi_{H_{ij}})\right) \quad (3)$$

where $\Delta\theta_i := \theta_i - \theta_i^0$, $\Delta P_{m_i} := P_{m_i} - P_{m_i}^0$, $K_{ij} := \frac{E_i E_j^0}{X_{ij}}\cos\delta_{ij}^0$, $\delta_{ij}^0 := \theta_i^0 - \theta_j^0$,

$$F_{ij} := \left(\left(E_j^1/E_j^0\right)^2 + \left(\theta_j^1\tan\delta_{ij}^0\right)^2 + 2\left(E_j^1/E_j^0\right)\theta_j^1\tan\delta_{ij}^0\cos\left(\phi_\theta + \phi_E\right)\right)^{-1/2}$$

$$\phi_{F_{ij}} := \tan^{-1}\left(\frac{\frac{E_j^1}{E_j^0}\sin\phi_E + \tan\delta_{ij}^0\theta_j^1\sin\phi_\theta}{\frac{E_j^1}{E_j^0}\cos\phi_E + \tan\delta_{ij}^0\theta_j^1\cos\phi_\theta}\right)$$

$$H_{ij} := \left(\left(\left(E_j^1/E_j^0\right)\tan\delta_{ij}^0\right)^2 + \left(\theta_j^1\right)^2 - 2\left(E_j^1/E_j^0\right)\theta_j^1\tan\delta_{ij}^0\cos\left(\phi_\theta + \phi_E\right)\right)^{-1/2}$$

$$\phi_{H_{ij}} := \tan^{-1}\left(\frac{\frac{E_j^1}{E_j^0}\tan\delta_{ij}^0\sin\phi_E - \theta_j^1\sin\phi_\theta}{\frac{E_j^1}{E_j^0}\tan\delta_{ij}^0\cos\phi_E - \theta_j^1\cos\phi_\theta}\right).$$

Thus, we obtain a differential equation with a time-varying coefficient from the original nonlinear model that takes into account the mutual effects of other synchronous machines. This is called a Mathieu equation, where we can see that the resonance frequency periodically varies. In this sense, the mutual effects are inherited from the original nonlinear model.

2.3 *Turbine and governor dynamics with saturation*

As we see in Figure 4, the turbine-governor system makes a mechanical input to the machine directly, hence it has large potential to enhance the stability of the power system. However, the dynamics of the turbine has large inertia, therefore it is impossible to drive it in a fast input change. Moreover, since the shaft of the turbine has a limit in torsion, the amplitude of the input must be limited to an adequate range. Hence, we have to take it into consideration in the design of the control system.

A simplified model of the turbine and governor system is described by

$$\dot{\xi}_{i1} = -\frac{1}{T_{T_i}}\xi_{i1} + \frac{1}{T_{T_i}}\xi_{i2} \quad (4)$$

$$\dot{\xi}_{i2} = -\frac{1}{T_{G_i}}\xi_{i2} + \frac{1}{T_{G_i}}u_i \quad (5)$$

where ξ_{i1} and ξ_{i2} represent outputs of the turbine and the governor respectively. T_{T_i} and T_{G_i} mean the time constants of them and those are listed in Table 2. The saturation of the turbine output can be formulated as

$$u_{G_{in}} = \mathrm{sat}_h\left(\xi_{i1}\right), \quad (6)$$

where the function $\mathrm{sat}_h(x)$ means

$$\mathrm{sat}_h(x) = \mathrm{sgn}(x)\min\left\{|x|, h\right\},\ h > 0.$$

3. CONTROL DESIGN

3.1 *A model for the control design*

The controller design is based on the differential equation with a time varying coefficient. Defining state-space values as

$$\begin{pmatrix} x_{i1} \\ x_{i2} \end{pmatrix} := \begin{pmatrix} \Delta\theta_i \\ \Delta\dot{\theta}_i \end{pmatrix} \quad (7)$$

the differential equation (3) is represented by

$$\begin{pmatrix} \dot{x}_{i1} \\ \dot{x}_{i2} \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ -(a_i + \frac{1}{M_i}\delta_i(t)e_i) & -\sigma_i \end{pmatrix}\begin{pmatrix} x_{i1} \\ x_{i2} \end{pmatrix} + \begin{pmatrix} 0 \\ \frac{1}{M_i} \end{pmatrix}\left(u_{G_{i1}} + \mathbf{p}_i\mathbf{d}_i^T(t)\right) \quad (8)$$

where a control input $u_{G_{i1}} := P_{m_i} - P_{m_i}^0$ is introduced, and σ_i, a_i, e_i, $\delta_i(t)$, $\mathbf{p}_i$ and $\mathbf{d}_i(t)$ are parameters represented by

$$\sigma_i := \frac{D_i}{M_i},$$

$$a_i := \frac{1}{M_i}\sum_{j=0,j\neq i}^{N} K_{ij},$$

$$e_i := \sum_{j=1,j\neq i}^{N} K_{ij}F_{ij},$$

$$\delta_i(t) := -e^{-\alpha t}\frac{\sum_{j=1,j\neq i}^{N} K_{ij}F_{ij}\cos\left(\omega t + \phi_{F_{ij}}\right)}{\sum_{j=1,j\neq i}^{N} K_{ij}F_{ij}}$$

$$\mathbf{p}_i := \left(K_{i,1}H_1 \ \cdots \ K_{i,i-1}H_{i-1} \ K_{i,i+1}H_{i+1} \ \cdots \ K_{i,N}H_N \right) \in \mathbb{R}^{1\times N-1}$$

$$\mathbf{d}_i(t) := e^{-\alpha t} \left(\cos\left(\omega t + \phi_{H_1}\right) \ \cdots \ \cos\left(\omega t + \phi_{H_{i-1}}\right) \ \cos\left(\omega t + \phi_{H_{i+1}}\right) \ \cdots \ \cos\left(\omega t + \phi_{H_N}\right) \right) \in \mathbb{R}^{1\times N-1}$$

Here, it should be noted that the following inequalities:

$$||\delta_i(t)|| \leq 1 \tag{9}$$

$$||\mathbf{d}_i(t)|| \leq \sqrt{N-1}e^{-\alpha t} \tag{10}$$

hold, where $|| \bullet ||$ denotes the Euclidean norm. On the other hand, the control input ξ_{i1} is created by a turbine-governor system represented in (4) and (5).

From (4) to (6) and (8), the plant for which we consider the control design is represented by

$$\dot{x}_i = (A_i + D_i\delta_i E_i)x_i + B_i\left[\mathrm{sat}_h(\xi_{i1}) + \mathbf{p}_i\mathbf{d}_i^T\right] \tag{11}$$

$$\dot{\xi}_{i1} = \alpha_{i1}\xi_{i1} + \beta_{i1}\xi_{i2} \tag{12}$$

$$\dot{\xi}_{i2} = \alpha_{i2}\xi_{i2} + \beta_{i2}u_i \tag{13}$$

where the state variable is defined by $x_i^T = \left(x_{i1} \ \ x_{i2}\right)$, parameters are

$$A_i = \begin{pmatrix} 0 & 1 \\ -a_i & -\sigma_i \end{pmatrix}, \quad B_i = D_i = \begin{pmatrix} 0 \\ 1 \\ \dfrac{1}{M_i} \end{pmatrix}$$

$$E_i = \left(e_i \ \ 0\right)$$

$$\alpha_{i1} = -\frac{1}{T_{T_i}}, \quad \beta_{i1} = \frac{1}{T_{T_i}}$$

$$\alpha_{i2} = -\frac{1}{T_{G_i}}, \quad \beta_{i2} = \frac{1}{T_{G_i}}.$$

3.2 *Control design for a partial system*

First, we consider the controller design for the system (11) in the absence of the saturation element. Here, ξ_{i1} is considered to be a fictitious input. It is possible to stabilize the system (11) by a linear state feedback controller, provided that the turbine output is small enough to be less than the saturation level.

Given $\mu_i > 0$, $\gamma_i > 0$ and $Q_i > 0$, we define a Riccati equation (ARE):

$$A_i^T P_i + P_i A_i + P_i\left(\mu_i D_i D_i^T - \frac{1}{\gamma_i}B_i B_i^T\right)P_i + \frac{1}{\mu_i}E_i^T E_i + Q_i = 0 \tag{14}$$

and a state feedback controller:

$$\xi_{i1} = -\left(\frac{1}{\gamma_i} + 2\kappa_i||\mathbf{p}_i||^2\right)B_i^T P_i x_i, \tag{15}$$

where P_i is a positive definite solution of the ARE (14), and κ_i is a free-parameter satisfying

$$\kappa_i \geq \frac{N-1}{4\alpha}. \tag{16}$$

By using the positive definite solution P_i, we also define an open ellipsoidal set:

$$\mathscr{E}(t^*) := \left\{ x_i \mid x_i^T P_i x_i < m_i e^{\eta_l t^*} - \frac{1-e^{-(2\alpha-\eta_l)t^*}}{2} \right\} \tag{17}$$

where

$$m_i = \frac{h^2}{\left(\frac{1}{\gamma_i} + 2\kappa_i||\mathbf{p}_i||^2\right)^2 ||B_i^T P_i^{\frac{1}{2}}||^2}$$

$$\eta_x = \sigma_{min}\left(Q_i P_i^{-1}\right)$$

$$\eta_\varepsilon = 2\alpha - \frac{N-1}{2\kappa_i}$$

$$t^* = \max\left\{\frac{1}{2\alpha}\ln\frac{2\alpha-\eta_l}{2m_i\eta_l}, 0\right\}$$

$$\eta_l = \min\{\eta_x, \eta_\varepsilon\}.$$

By using these items, we obtain the following results. Due to space limitations the proofs of the results have been omitted, instead, those appear in (T. Watanabe, 2002).

Theorem 1 (Low gain controller)
Suppose that the ARE (14) has a positive definite solution P_i. Then, if the initial condition satisfies $x_i(0) \in \mathscr{E}(t^*)$, the origin of the closed loop system that is composed of (11) and the state feedback controller in (15) is locally asymptotically stable, where the amplitude of the control input satisfies

$$|\xi_{i1}(x_i(t))| < h, \quad \forall t \in [0, \infty). \tag{18}$$

Remark 1. In this design, the saturation of the turbine output is avoided by making the control input small. However, in this case we obtain a conservative result, not fully using the control capacity of the turbine-governor control system. On the other hand, in (Saberi *et al.*, 1999; Dona *et al.*, 1999) it is shown that if we allow an actuator to saturate, we can obtain a better performance of the control system.

In the next result, we consider an over-saturation design of the turbine-governor system to make full use of the power for damping low-frequency oscillations in power systems.

Theorem 2 (High gain controller)
Suppose that the ARE (14) has a positive definite solution P_i, and for an a priori given bounded set $\mathscr{X}_0$ there exists a κ_i in $\left[\frac{N-1}{4\alpha}, \infty\right)$ such that $\mathscr{X}_0 \subseteq \mathscr{E}$. Then, the equilibrium point of the closed loop system composed of (11) and

$$\xi_i(t) = -(1+\rho_i)\left(\frac{1}{\gamma_i} + 2\kappa_i||\mathbf{p}_i||^2\right)B_i^T P_i x_i, \tag{19}$$

where $\rho_i \geq 0$, is locally asymptotically stable with $\mathscr{X}_0$ contained in its basin of attraction.

3.3 *Backstepping design*

The robust controller obtained in the above theorem generates idealized value of the mechanical input that locally stabilizes the system (11) in the presence of saturation nonlinearity in the input. However, a required controller directly makes the input to the governor, and then through the dynamics of the turbine-governor system, generates the mechanical input to the machine indirectly. Hence, we have to take the dynamics of the turbine-governor system into account in the controller design. To this end, we introduce the technique of backstepping (Khalil, 1996; Teel and Praly, 1995) to compensate the dynamics of the turbine and governor system. We denote the control input (19) by

$$\mu(x_i) := -(1+\rho_i)\left(\frac{1}{\gamma_i} + 2\kappa_i \|\mathbf{p}_i\|^2\right) B_i^T P_i x_i. \quad (20)$$

Theorem 3
Suppose that the controller $\xi_{i1} = \mu(x_i)$ locally stabilizes the origin of the system (11) with $\mathscr{X}_0$ contained in its basin of attraction, where $\mathscr{X}_0 \subseteq \mathscr{E}$ is an a priori given bounded set. Then, for all $(x_i(0), z_i(0)) \in \mathscr{X}_0 \times \mathscr{Z}$ where $\mathscr{Z} \subseteq \mathbb{R}^2$ is an arbitrary bounded set, there exist positive real numbers k_{i1}^* and k_{i2}^* such that for each k_{i1} and k_{i2} with $k_{i1} \geq k_{i1}^*$ and $k_{i2} \geq k_{i2}^*$ the equilibrium $(x_i, z_i) = (0,0)$ of the closed loop system represented by (11) to (13) and

$$u_i = -\frac{k_{i2}(k_{i1}+\alpha_{i1}) + \beta_{i1}^2}{\beta_{i1}\beta_{i2}}\xi_{i1} - \frac{k_{i2}+\alpha_{i2}}{\beta_{i2}}\xi_{i2} + \frac{k_{i1}k_{i2}+\beta_{i1}^2}{\beta_{i1}\beta_{i2}}\mu(x_i) \quad (21)$$

is locally asymptotically stable with $\mathscr{X}_0 \times \mathscr{Z}$ contained in its basin of attraction.

Remark 2. When $\rho_i = 0$ is used, we call (21) the low-gain robust controller, and when $\rho_i > 0$, we call (21) the high-gain robust controller.

4. DESIGN EXAMPLES

Using the above results, we design controllers for a two-machine-quasi-infinite-bus system that is obtained from Figure 1 by replacing the infinite bus with an quasi-infinite bus where it is assumed that the bus voltage and the phase angle vary, expressing oscillations in the external network. Here, we assume that the voltage and the phase angle of the quasi-infinite bus varies as

$$E_B = E_B^0 + E_B^1 e^{-\alpha t}\sin(2\pi f t) \quad (22)$$

$$\theta_B = \theta_B^0 + \theta_B^1 e^{-\alpha t}\sin(2\pi f t). \quad (23)$$

The system parameters in Table 1 and $E_B^0 = 1.0$, $E_B^1 = 0.1$, $\theta_B^0 = 0.0$, $\theta_B^1 = 0.1$, $\alpha = 0.5$, $f = 0.5$[Hz] are used. Also, parameters that we use to design the controllers are $\mu_1 = 0.66 \times 10^{-3}$, $\mu_2 = 1.0 \times 10^{-3}$, $\gamma_1 = 1500$, $\gamma_2 = 1000$, $\kappa_1 = 2.0$, $\kappa_2 = 3.5$, $Q_1 = I_2$, $Q_2 = 0.1I_2$, $k_{11} = k_{21} = 200$, $k_{12} = k_{22} = 600$.

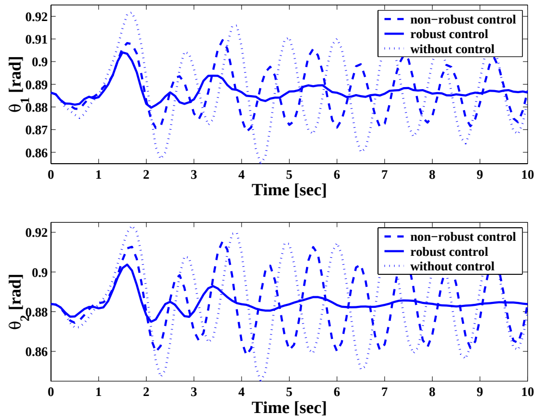

Fig. 5. Responses of phase angles

4.1 *Low-gain robust controller*

In order to verify control performance of the proposed low-gain robust control, responses of phase angles with the perturbations in (22) and (23) are investigated in both systems compensated by the proposed low-gain robust controller and a non-robust controller respectively. The non-robust controller is obtained from the model represented by (11) to (13) where the time-varying parameter $\delta_i(t)$ is put to zero. These are plotted in Figure 5. We can see that the robust controller damps the oscillation efficiently in each machine.

Next, we demonstrate that the maximal amplitude of the turbine output is adjustable by tuning the parameter κ_i. Here, parameters except κ_i are same as in the above example. κ_i are changed as $\kappa_1 = 4.0, 2.0, 1.0$ and $\kappa_2 = 7.0, 3.5, 1.75$, where the minimal value to satisfy the stability of the controlled system is evaluated as $\kappa_i \geq 1$. Figures 6 and 7 illustrate responses of the turbine output ξ_i and the phase angle θ_i. We can verify that the maximal output reduces as κ_i decreases, whereas the transient response of θ_i deteriorates.

4.2 *High-gain robust controller*

Parameters that are used to obtain high-gain robust controllers are same as what are used in the above example except for κ_i and ρ_i. Here, we assume that the saturation level of each turbine output is 1.5×10^{-2} [p.u.] respectively. Then, we select the parameters κ_i as $\kappa_1 = 2.0$ and $\kappa_2 = 3.5$, and ρ_i as $\rho_1 = 20$ and $\rho_2 = 15$. Figures 8 and 9 show that the high-gain robust controller improves the damping of the closed loop system by allowing saturation of turbine output.

5. CONCLUSION

This paper has presented a new model for the designing of the turbine-governor control system, where the

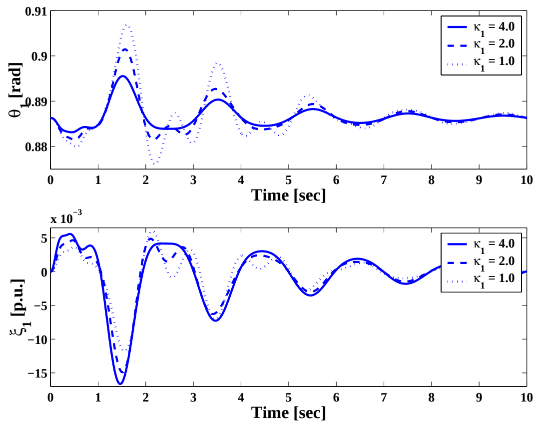

Fig. 6. Responses of phase angles and turbine outputs of the #1 machine

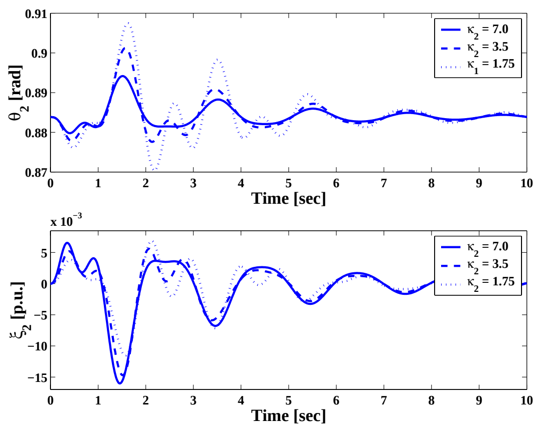

Fig. 7. Responses of phase angles and turbine outputs of the #2 machine

mutual effects of machines are taken into account. Also, the control design that incorporates constraints due to saturation nonlinearity of the turbine output is proposed. Some preliminary examples have shown that the effectiveness of using the proposed model as well as this design.

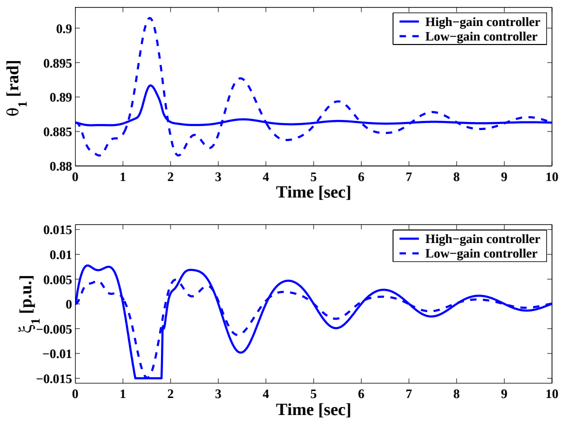

Fig. 8. Responses of phase angles and turbine outputs of the #1 machine

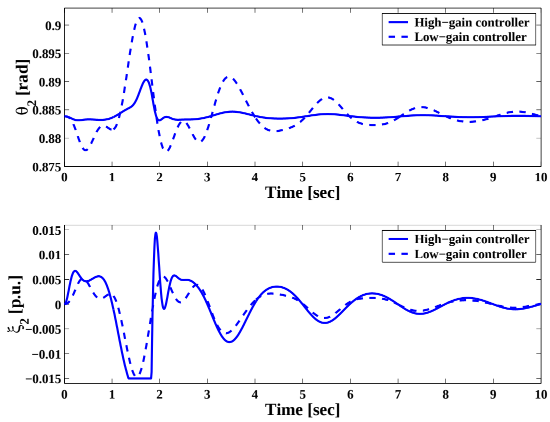

Fig. 9. Responses of phase angles and turbine outputs of the #2 machine

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