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Wide-range reliable stabilization of time-delayed power systems

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Abstract: Steam valve control is usually discarded in power system stability due to belief in its slow response. The present manuscript makes use of it as a backup control in the case of failure of the main fast excitation control. The model describing system dynamics as a function of the two controllers, with wide range loading conditions, is derived in a norm-bounded format. Linear matrix inequalities are derived as a sufficient condition to obtain reliable controllers that provide good oscillation damping when both controllers are sound or even in the case of failure of either one. The design scheme is robust in the sense that it keeps reliable stability against wide load changes as well. A single machine infinite bus system is presented to illustrate the proposed design procedure and exhibit its performance. Results of excitation and governor controller testing show that the desired performance could be fulfilled from light load to heavy load conditions. System performance shows a remarkable improvement of dynamic stability by obtaining a well-damped oscillation time response even in the case of failure of either controller. Extension of the proposed controller to multiarea load-frequency control with time delay is also presented.

Key words: Power system stability, excitation control, steam valve control, linear matrix inequalities, robust control, reliable control, time-delay systems, load-frequency control

1. Introduction

Enhancing power system stability is of great importance, since loss of stability, power separation, and collapse may cause serious damage to national economy and personal comfort. Generators are usually equipped with a thyristor-controlled static exciter due to its rapidity and high reliability. The terminal voltage deviation from a reference value is used to regulate the terminal voltage of generators using proportional (P) or proportional integral derivative (PID) controllers to obtain a control-automatic voltage regulator AVR. However, the AVR may have an adverse effect on system stability for large closed-loop gains of the excitation channel. This problem is solved by injecting an additional stabilizing signal generated by power system stabilizers (PSSs), whose input is usually the speed deviation of the generator.

Many PSS designs exist in the following studies and references therein. A single or double lead stage control using frequency response and root locus methods was presented in [1,2], while [3] provided coordinated design of the AVR-PSS. Linear optimal control is found in [4]. Robust control to consider the uncertainty due to load variations is presented in [5–8]. In [9], resilient control was given to cope with uncertainties due to both load variations and controller parameters errors. Note that in [9], nonlinear system dynamics are represented by a

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linearized model with uncertainty approximated by a norm-bounded form. Without such approximation, many works exist for nonlinear excitation control as follows: fuzzy-logic control was used in [10], adaptive control was presented in [11], adaptive fuzzy PSS was given in [12] while [13] deals with feedback linearization, an energy-shaping technique was proposed in [14] while [15,16] presented back-stepping and sliding mode methods, and application of wavelet networks to power system stabilizer design was presented in [17].

It is worth mentioning that the above excitation controllers suffer from a severe shortcoming, the failure of that controller. The idea of controlling a system by two controllers is better than using only one and results in what is termed reliable or fault-tolerant control, as currently used for different systems as switching systems [18,19]. The main objective of this technique is that, in the case of failure of either controller, or no failure, stability of the system is kept. Further stability enhancement is achieved by making use of flexible AC transmission systems (FACTS). In this context, [20] presents reliable stabilization to consider the case of failure of either excitation-PSS or FACTS controllers.

As an alternative to FACTS, governor control should not be ruled out as a backup controller for excitation control. Valve control for hydraulic turbines is not so effective in stability improvement due to the water hammer while steam valve control can be. Modern electrical-hydraulic governors have replaced the old slow mechanical-hydraulic ones. The dead band of modern steam valves is only 0.1 to 0.2 s [21]. Steam governor control with its inherent time delay was used in [22] as a back up to the excitation control without considering load variation. Fast valving and braking resistors for enhancing power system transient stability are applied as presented in [23,24].

In this paper, robust reliable stabilization using excitation and governor controllers is designed in the presence of state delay. The proposed controller is designed in the state feedback form. It is proved that the controller guarantees robust stability against load variations and controller failure. The advantage of the controller is that it maintains the desired swiftness of the response even if failure occurs for either the excitation or governor channel. Extension to time-delay multiarea load-frequency control is also presented.

The manuscript is organized as follows. The power system dynamic model and problem formulation are given is Section 2. Section 3 presents a robust reliable control for uncertain linear systems with time delay in the states. Testing of the proposed controller on the case study of a single-machine infinite-bus (SMIB) and time-delay two-area load-frequency control (LFC) system is given in Section 4. Concluding remarks are given in Section 5.

Notations: We use I, W', and W^{-1} to denote respectively the identity matrix, transpose, and inverse of a square matrix W. W >0 (W <0) means positive- (negative-)definite matrix W. The symbols $\|(.)\|$ and $\bullet$ denote respectively the norm of (.) and an ellipsis for terms in matrix expressions that are induced by symmetry, i.e.:

$$\begin{bmatrix} L+W+M+W'+M' & N \\ \bullet & R \end{bmatrix} = \begin{bmatrix} L+(W+M+\bullet) & N \\ N' & R \end{bmatrix}$$

Fact 1: For any real matrices W_1, W_2 and $\Delta(t)$ with appropriate dimensions and $\Delta\Delta' < I$, it follows that [25]:

$$W_1\Delta(t)W_2 + \bullet < \varepsilon W_1 W_1^{'} + \varepsilon^{-1} W_2^{'} W_2, \varepsilon > 0 \tag{1}$$

where $\Delta(t)$ represents system uncertainties with bounded norm, i.e. $\|\Delta(t)\| < 1$.

2. Power system model and problem formulation

In this section, we derive the linear dynamic model of a single machine connected to an infinite bus through a transmission line [1]. The block diagram of such a system is shown in Figure 1.

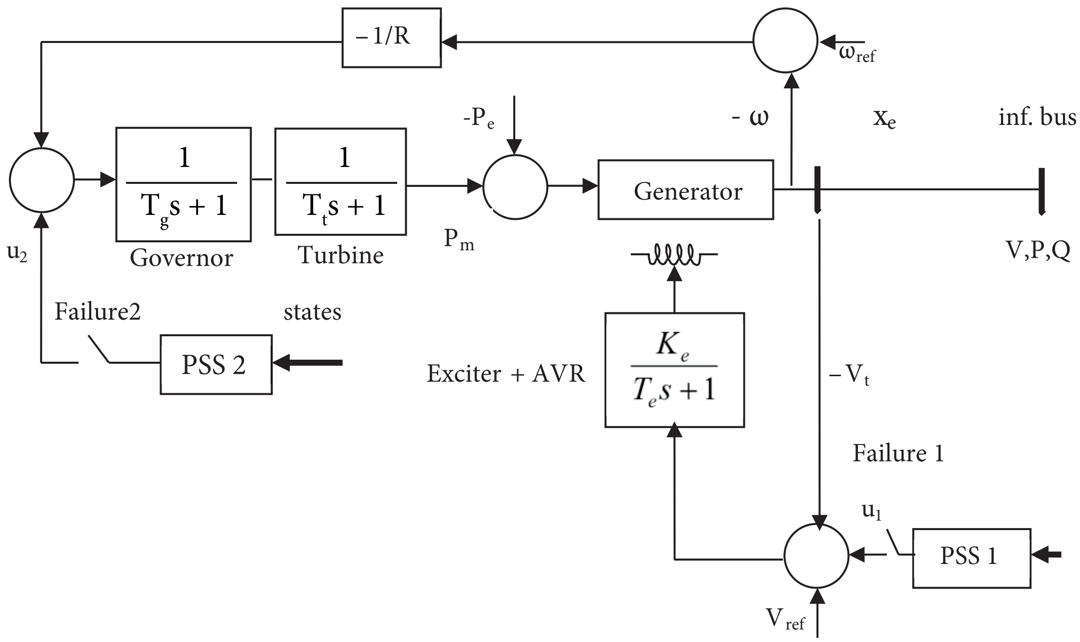


Figure 1. Single machine infinite bus system (SMIB) with possible failure of u_1 or u_2.

It should be emphasized that the infinite bus could be representing the Thévenin equivalent circuit of a large interconnected power system. The machine is equipped with a static (thyristor) exciter and is assumed to be of the nonreheat type. It is assumed that the machine is also equipped with excitation and steam valve control. The nonlinear dynamic model of the SMIB is given by five first-order differential equations where the fourth equation represents the AVR and exciter, while the fifth equation describes the governor dynamics [1]:

$$\begin{aligned}
&\dot{\delta} = \omega_o(\omega - \omega_o) = \omega_o \Delta\omega \\
&\Delta\dot{\omega} = \tfrac{1}{2H}[P_m - P_e] \\
&\dot{E}'_{qo} = \tfrac{1}{T'_{do}}[E_f - \{E'_q + (x_d - x'_d)I_d\}] \\
&\dot{E}_f = \tfrac{1}{T_e}[-E_f + K_e(V_{ref} - V_t + u_1)] \\
&\dot{P}_m = \tfrac{1}{T_{gt}}[-P_m - \tfrac{1}{R}\Delta\omega(t-\tau) + u_2]
\end{aligned} \tag{2}$$

where u_1, and u_2 represent respectively the excitation and governor control. Note that

$$P_e = V_d I_d + V_q I_q \tag{3}$$

with V_q and V_d given by:

$$\begin{aligned}
V_q &= E_q - (x_d + x_e)I_d \\
V_d &= (x_q + x_e)I_q
\end{aligned} \tag{4}$$

Now using Eq. (4) in Eq. (3) obtains the following:

$$P_e = [E_q + (x_q - x_d)I_d]I_q$$

The output power P_e can also be written in terms of the direct-axis transient reactance as

$$P_e = [E_q^{'} + (x_q - x_d^{'})I_d]I_q \tag{5}$$

I_d, I_q, and V_d are given by:

$$I_d = (E_q' - V\cos\delta)/(x_d' + x_e)$$
$$I_q = V\sin\delta/(x_q + x_e)$$
$$V_t = \sqrt{(I_q x_q)^2 + (E_q' - I_d x_d')^2}$$

The definitions of symbols are given in the Appendix [1,2].

Substituting Eq. (5) in Eq. (2) and then linearizing around an operating point (δ_o, $\omega_o, E_{qo}^{'}, E_{fd}$, P_{mo}) (letting $\Delta\delta = \delta - \delta_o, \ldots$.etc.), the following linearized model is obtained:

$$\dot{x}(t) = (A + \Delta A)x(t) + A_d x(t - \tau) + Bu \tag{6}$$

where $x = [\Delta\delta, \Delta\omega, \Delta E_q^{'}, \Delta E_{fd}, \Delta P_m]$ with initial conditions $x(t) = x_o, t \in [-\tau, 0]$,

$$A = \begin{bmatrix} 0 & \omega_o & 0 & 0 & 0 \\ -\frac{k_1}{2H} & 0 & -\frac{k_2}{2H} & 0 & \frac{1}{2H} \\ -\frac{k_4}{T_{do}^{'}} & 0 & -\frac{1}{T} & \frac{1}{T_{do}^{'}} & 0 \\ -\frac{k_5 k_e}{T_e} & 0 & -\frac{k_6 k_e}{T_e} & -\frac{1}{T_e} & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{T_{gt}} \end{bmatrix}, A_d = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{-1}{T_{gt}R} & 0 & 0 & 0 \end{bmatrix}, B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ \frac{k_e}{T_e} & 0 \\ 0 & \frac{1}{T_{gt}} \end{bmatrix}$$

and the matrix ΔA represents system uncertainty due to load variations, which can be represented in a norm-bounded format as $\Delta A = M_x \Delta N$. The uncertainty matrices M and N can be easily calculated using the singular value decomposition. The parameters k_1 to k_6 are expressed in terms of the machine load (P, Q) and can be found in [5].

The control objective can be stated as follows: design robust reliable stabilization controllers for the system given in Eq. (6) for different load conditions. The reliability in this context means that one control signal, either u_1 or u_2, should be able to robustly stabilize the system. Therefore, the following cases are considered:

1- Only controller u_1 is active (u_2 fails).

2- Only controller u_2 is active (u_1 fails).

3- Both controllers are active (no failure).

The case of simultaneous failure of both controllers is excluded since it is very unlikely in practice.

The above cases are respectively represented by the following input matrices:

$$B_1 = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ \frac{k_e}{T_e} & 0 \\ 0 & 0 \end{bmatrix}, B_2 = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & \frac{1}{T_{gt}} \end{bmatrix}, B_3 = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ \frac{k_e}{T_e} & 0 \\ 0 & \frac{1}{T_{gt}} \end{bmatrix}$$

In addition to the required reliable stabilization for the above three cases, the oscillations have to be damped out within 10 to 15 s over different load conditions as required by power engineers [26]. In other words, the uncertain state-delay system of Eq. (6) is said to be robustly stabilized with degree of stability α >0 if there exists a state-feedback control $u(t) = Fx(t)$, where F is a feedback gain matrix to be determined later, such that the closed-loop system response satisfies the following:

$$\|x(t)\| < \|x(0)\| \, e^{-\alpha . t}, t > 0 \tag{7}$$

3. Design of robust reliable control

This section presents a method for designing a robust and reliable controller to ensure asymptotic stability of the closed-loop system with degree α for all admissible uncertainties as well as actuator faults. The main contribution of this paper is stated in the following theorem.

Theorem *The state-time delay system given in Eq. (6) is robustly stable with degree α for different controller failures by a state feedback control $u = Fx$ if there exists a feasible solution to the following LMIs:*

$$\left.\begin{array}{l} Y = Y' > 0, S = S' > 0, Z = Z' > 0, \varepsilon > 0 \\ \begin{bmatrix} \{(A+\alpha I)Y + B_i L + \bullet\} + Z + \varepsilon M_x M_x' & A_d e^{\alpha\tau} & YN' \\ \bullet & -S & 0 \\ \bullet & \bullet & -\varepsilon I \end{bmatrix} < 0, i = 1,2,3 \end{array}\right\} \tag{8}$$

where $Y = P^{-1}, L = FY, Z = YSY$. The controller gain matrix is then calculated as $F = LY^{-1}$.

Proof The closed-loop system takes the following form:

$$\dot{x} = (A + \Delta A + B_i F)x + A_d x(t-\tau), i = 1,2,3 \tag{9}$$

Using the transformation $x = e^{-\alpha t} z, t > 0$ [27] yields the following equivalent representation of Eq. (9):

$$\dot{z} = (A + \Delta A + B_i F + \alpha I)\, z + e^{\alpha\tau} A_d z(t-\tau) \tag{10}$$

The uniform asymptotic stability of Eq. (10) guarantees the α uniform asymptotic stability of the closed-loop system of Eq. (9).

Now consider the following Lyapunov–Krasovskii function:

$$V(t) = z'(t)Pz(t) + \int_{t-\tau}^{t} z'(\theta)Sz(\theta)d\theta \tag{11}$$

where $P = P' > 0, S = S' > 0$.

The time derivative of Eq. (11) is obtained as:

$$\dot{V}(t) = \dot{z}'Pz + zP\dot{z} + z'Sz - z'(t-\tau)Sz(t-\tau) \tag{12}$$

To ensure stability of the system of Eq. (10), the derivative of $V(t)$ must be negative definite, i.e. $\dot{V}(t)$ <0. Along the trajectory of Eq. (10), this condition can be written as:

$$\begin{bmatrix} z \\ z(t-\tau) \end{bmatrix}' \begin{bmatrix} \{P(A+\Delta A+B_iF+\alpha I)+\bullet\}+S & PA_de^{\alpha\tau} \\ \bullet & -S \end{bmatrix} \begin{bmatrix} z \\ z(t-\tau) \end{bmatrix} < 0 \tag{13}$$

Pre- and postmultiplying Eq. (13) by diag. $[P^{-1}, I]$, letting $P^{-1} = Y, FP^{-1} = L$, and using Eq. (1), the LMI of Eq. (8) is obtained. This completes the proof. □

4. Simulation results

The validity of the proposed robust reliable stabilization control is examined via two simulation examples, namely reliable robust excitation/governor control and reliable robust LFC of a two-area time-delay system.

4.1. Reliable robust excitation/governor control

In this example, robust reliable stabilization for a state-delayed SMIB is designed using excitation and governor controllers. The numerical parameters of the system are given in Table 1. and the loading conditions of interest are shown in Table 2.

Table 1. Numerical parameters of SMIB power system.

Synchronous machine	$x_d = 1.6, x_d' = 0.32, x_q = 1.55, \omega_o = 2\pi \times 50 rad/s,$ $T_{do}' = 6s, 2H = 10s, V = 1$
Exciter-amplifier	K_e = 50, T_e = 0.05 s,
Governor-turbine	T_{gt} = 1 s, R =0.05
Transmission line	x_e = 0.4
Governor time delay	τ = 1 s

Table 2. Loading conditions of SMIB power system.

Loading P (p.u.)	Q (p.u.)
Heavy 1	0.5
Nominal 0.7	0.3
Light 0.4	0.1

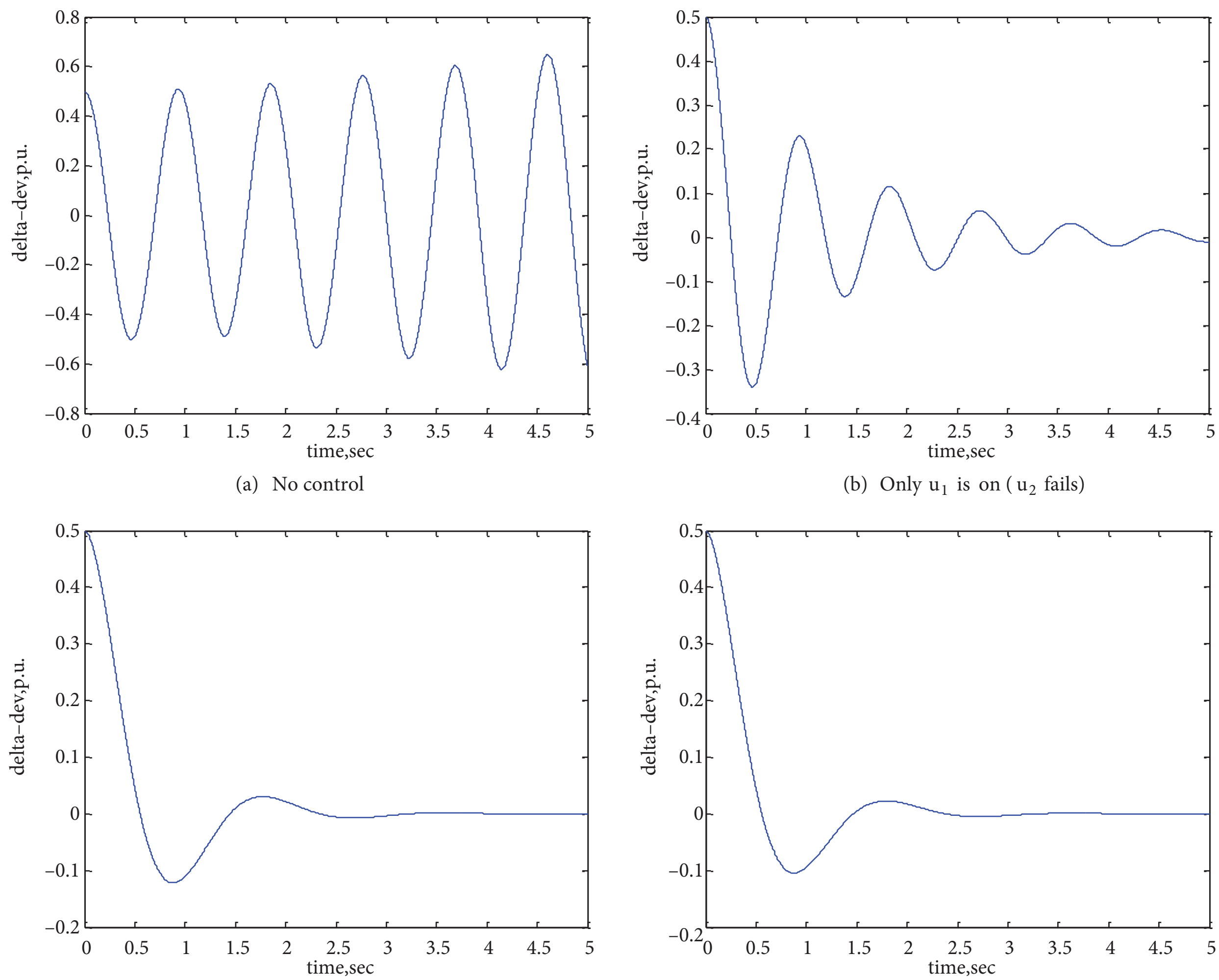
At nominal load, the system matrix A is determined as:

$$A = \begin{bmatrix} 0 & 314 & 0 & 0 & 0 \\ -0.1186 & 0 & -0.0906 & 0 & 0.1 \\ -0.1933 & 0 & -0.4633 & 0.1667 & 0 \\ -11.864 & 0 & -511.6 & -20 & 0 \\ 0 & 0 & 0 & 0 & -1 \end{bmatrix}$$

Using singular value decomposition [25], the uncertainty matrices M and N are calculated as M_x = [0, 0, 0, 6.63, 0]', N = [6.63, 0, –2.1, 0, 0]. Therefore, the LMI of Eq. (8) is solved using the LMI control toolbox. It has a feasible solution and the robust reliable state feedback matrix F is found to be:

$$F = \begin{bmatrix} -1.0521 & 35.126 & -2.222 & -0.057131 & 1.1765 \\ 405.19 & -13580 & 866.54 & 22.497 & -452.01 \end{bmatrix}$$

The proposed controller is tested at extreme loads when a 0.5 rad change in the torque angle due a cleared fault at the machine terminal is considered. The following numerical experiments are carried out using Simulink. When heavy load is applied, simulation results for open-loop, for excitation control (u_1) only, for steam valving control (u_2) only, and for both controllers are shown in Figure 2. Similarly, for light load, the responses are shown in Figure 3. As seen from Figures 2 and 3, the system is poorly damped or even unstable for extreme loads. A remarkable stability improvement is achieved using the proposed controllers, achieving damped oscillations within the desired settling time. Consequently, the proposed controller achieves robust stabilization against load variations and reliability against failure of either excitation or steam valving control channels.



(a) No control

(b) Only u_1 is on (u_2 fails)

(c) Only u_2 is on (u_1 fails)

(d) Both u_1 and u_2 are on (no failure)

Figure 2. $\Delta\delta$ (p.u.) - time (s) (heavy load).

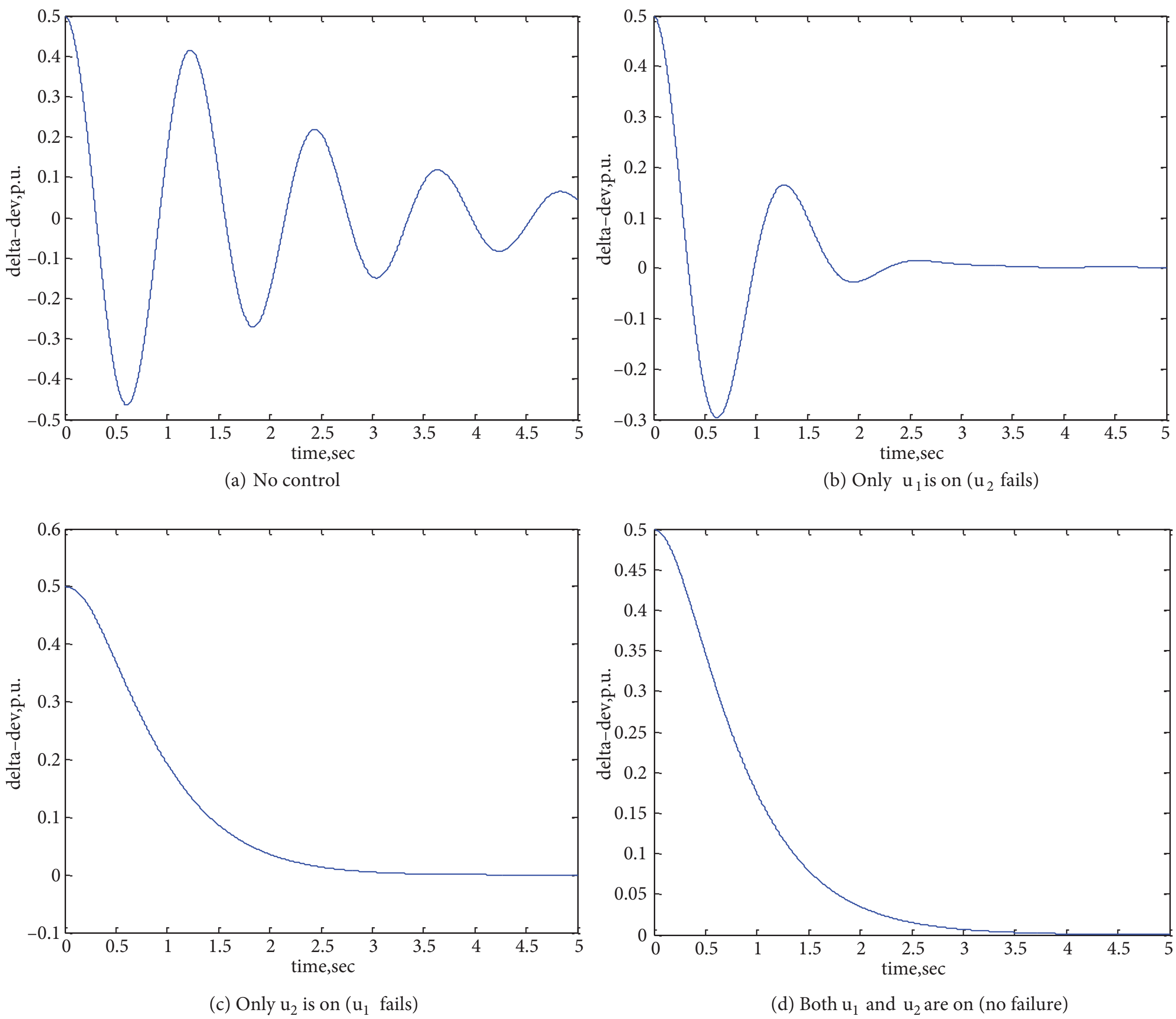


Figure 3. $\Delta\delta$ (p.u.) - time (s) (light load).

4.2. Two-area time-delay load-frequency control: reliability and robustness

The operation objectives of LFC, also called automatic generation control (AGC), are to maintain system frequency and the tie-line power as close as possible to the scheduled values [28]. Traditionally, communication delays of control signals in LFC are neglected. This becomes unacceptable due to deregulation in power systems [29,30]. The communication delays can be classified into two types: random and constant. The random delays, from the sensors to the control center, range from 0.1 to 0.7 s depending on the communication route, protocol, malicious attacks, etc. The constant delays from the control center to the generators represent a heavily congested communication network with packets dropped; in USA the control signal is sent to generators every 4 s. In this example, the LFC of a two-area power system is considered and extension to multiarea is straightforward. The proposed robust reliable control is applied to each area. The mathematical model of a two-area LFC considering the time delay can be written as:

$$\dot{x} = Ax + A_d x(t-\tau) + Bu + \Gamma \Delta P_d \tag{14}$$

where $x = [\Delta\omega_1, \Delta P_{m1}, \Delta E_1, \Delta\omega_2, \Delta P_{m2}, \Delta E_2, \Delta P_{12}]'$ is the state vector, u is the control vector, and ΔP_d is the load demand.

$$A = \begin{bmatrix} -\frac{D_1}{M_1} & \frac{1}{M_1} & 0 & 0 & 0 & 0 & -\frac{1}{M_1} \\ -\frac{1}{T_{gt1}R_1} & -\frac{1}{T_{gt1}} & 0 & 0 & 0 & 0 & 0 \\ -k_1B_1 & 0 & 0 & 0 & 0 & 0 & -k_1 \\ 0 & 0 & 0 & -\frac{D_2}{M_2} & \frac{1}{M_2} & 0 & \frac{1}{M_2} \\ 0 & 0 & 0 & -\frac{1}{T_{gt2}R_2} & -\frac{1}{T_{gt2}} & 0 & 0 \\ 0 & 0 & 0 & -k_2B_2 & 0 & 0 & k_2 \\ P_s & 0 & 0 & -P_s & 0 & 0 & 0 \end{bmatrix} \text{ and } B = \begin{bmatrix} 0 & 0 \\ \frac{1}{T_{gt1}} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & \frac{1}{T_{gt2}} \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

$$A_d = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{T_{gt1}} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{T_{gt2}} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}, \Gamma = \begin{bmatrix} \frac{-1}{M_1} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & \frac{-1}{M_2} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

The definitions of symbols and parameter values are given in [28] and listed in Table 3. The tie-line synchronizing power is $P_s = 2$.

Table 3. Data of 2-area LFC.

Area	1	2
Speed regulation, R	0.05	0.0625
Frequency sensitivity load coefficient, D	0.6	0.9
Inertia constant, M;	10	8
Base power, MVA	1000	1000
Governor-turbine time constant, T_{gt}	0.7	0.9
Constant of integral control, k	0.3	0.3

The block diagram of the system given in Eq. (14) is shown in Figure 4. It is worth mentioning that the governor and turbine are approximated as a single time constant and the delay is lumped as a single delay $\tau =$ 4 s [29,30]. With desired $\alpha = 0.2$, assuming $M = N = 0$ (since no uncertainty is considered in the LFC) and solving Eq. (8), the state feedback gain matrix for the reliable controller is given by:

$$F = \begin{bmatrix} -25.1131 & -2.1363 & 4.6467 & 10.7586 & 0.7249 & -2.4279 & 4.1920 \\ 21.2299 & 1.3209 & -3.4511 & -23.0798 & -2.4592 & 5.7108 & -5.3015 \end{bmatrix}$$

A load disturbance of 0.5 p.u. is assumed to take place in area 1. Simulation results with activation of integral control only are shown in Figure 5. When the proposed controller is applied to both areas, the results are as shown in Figure 6. When one of the proposed controller experiences a failure, the results are as shown in Figure 7 (controller of area 1 is active) and Figure 8 (controller of area 2 is active). As seen, the proposed control has tight control grip when only u_1 is active or when both u_1 and u_2 are on. However, when only u_2 is active, it has less control effect since the load disturbance occurs in area 1.

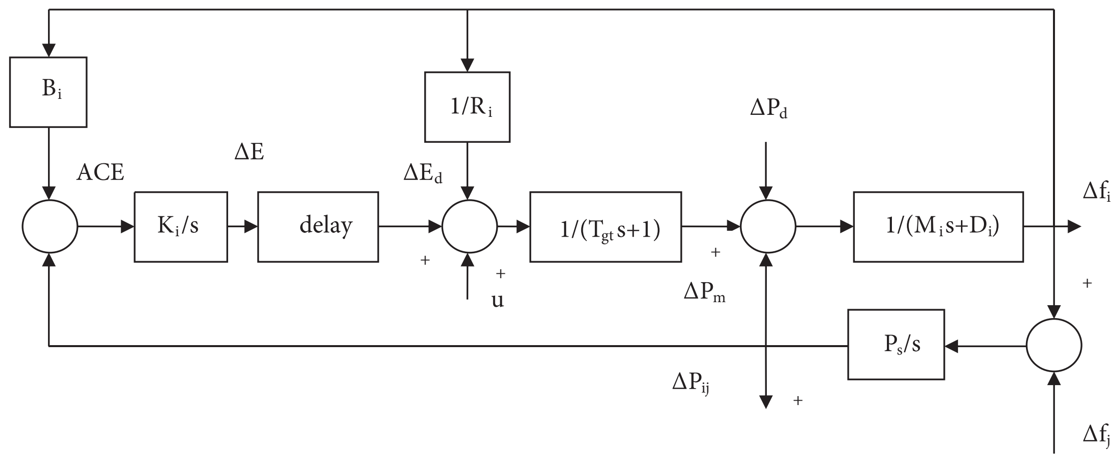


Figure 4. Multiarea load-frequency control system.

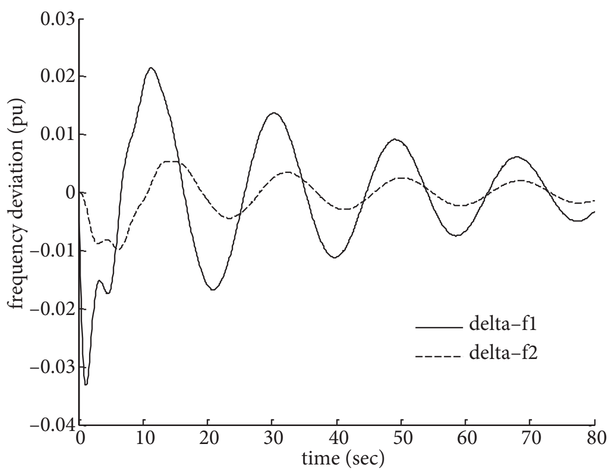


Figure 5. Frequency deviation in the two areas when only the integral control is active.

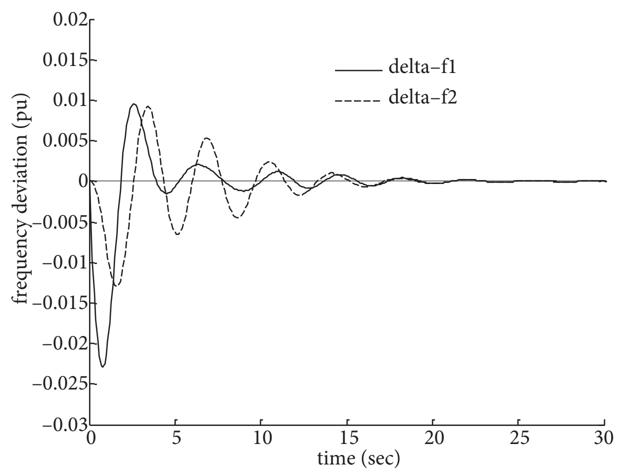


Figure 6. Frequency deviation of the two areas when the proposed controller in both areas is on.

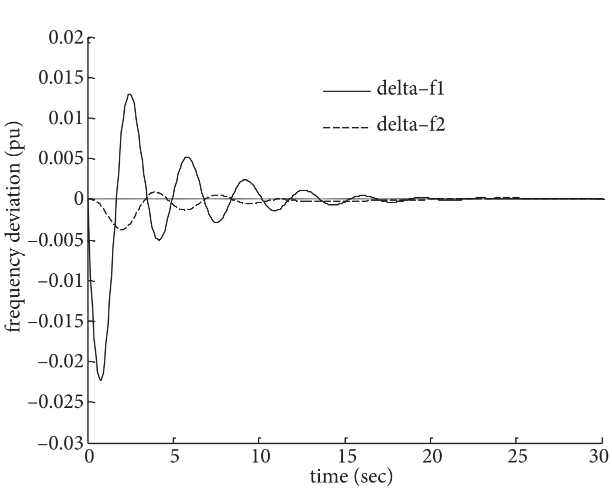


Figure 7. Frequency deviation of the two areas when the proposed controller of area 1 is on.

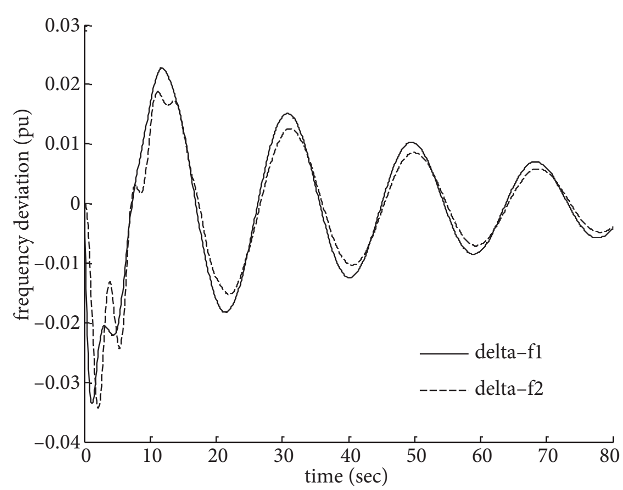


Figure 8. Frequency deviation of the two areas when the proposed controller of area 2 is on.

5. Conclusion

The main contribution of this paper is presenting a simple design procedure of robust reliable control for time-delay power systems. Two cases of actuator faults (excitation and governor) are considered. The resulting state feedback controllers guarantee robust reliable stability with desired settling time for different loads and failure of either controller channel. The proposed controller is also tested to design reliable load-frequency control channels for a two-area power system. Simulation results prove the superiority of the designed controller in achieving desired dynamic performance while securing the operation against controller failure.

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Appendix List of symbols

All data are per unit (p.u.) unless otherwise stated.

P_m Mechanical power.

$x_d^{'}$ Generator direct-axis transient reactance.

x_d, x_q Direct and quadrature-axis synchronous reactance, respectively.

x_e Transmission line reactance.

$T_{do}^{'}$ d-axis open circuit field time constant (s).

H Inertia constant (s).

δ Torque angle between machine internal voltage and infinite bus voltage (rad).

ω Angular velocity.

E_{fd} Field voltage.

$E_q^{'}$ q-axis voltage behind transient reactance.

u_1 Excitation control signal (PSS output), or control input of area 1.

K_e, T_e Exciter-amplifier gain and time constant.

u_2 Steam valving control signal, or control input of area 2.

R Speed droop.

T_{gt} Governor-turbine time constant (s).

τ Time delay.

V Infinite bus voltage.

P, Q Machine load.