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Effect of Time Delay Asymmetries in Power System Damping Control

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***Abstract*—Distributed control compensation based on local and remote sensor feedback can improve small-signal stability in large distributed systems, such as electric power systems. Long distance remote measurements, however, are potentially subject to relatively long and uncertain network latencies. In this work, the issue of asymmetrical network latencies is considered for an active damping application in a two-area electric power system. The combined effects of latency and gain are evaluated in time domain simulation and in analysis using root-locus and the maximum singular value of the input sensitivity function. The results aid in quantifying the effects of network latencies and gain on system stability and disturbance rejection.**

***Index Terms*—Inter-area oscillations, damping control, small-signal stability, time delay, communication latencies**

I. Introduction

Power systems that are sparsely connected, have long transmission lines, and/or are heavily loaded are often affected by oscillations that limit their power transfer capabilities. These oscillations are the result of energy swing exchanges between groups of generators and are referred to as inter-area oscillations or modes. Adequate damping of these swings is critical to the performance and security of a power system.

Traditionally, damping of inter-area oscillations is carried out by attaching local controllers to the generating units that have the greatest controllability of the mode. Power system stabilizers (PSSs) are the most widely used type of (local) controller deployed towards that end. In addition to PSSs, other power system components can be used to provide damping to inter-area modes, such as Thyristor-controller Series Compensators (TCSCs) [1]–[3], Static Var Compensators (SVCs) [2], [4] and energy storage [5].

The damping of these oscillations using system-wide information has also been investigated through Wide Area Damping Control (WADC) schemes using different power system components as actuators for these control strategies. PSSs with remote signals have been studied in [6] and WADC using wind generators in [7]. Because power systems subject to inter-area power swings cover large geographic areas, the use of system-wide information requires robust communication networks. Even if the communication channels used for transmitting the information needed for the wide-area control strategy are completely reliable, the information being transmitted can still be subject to high communication latencies. The study of the impact these latencies have on the dynamics of the power system is critical for an adequate wide-area control design. The works in [8], [9] show the effect that individual latencies have on power system damping and frequency controllers.

In this paper, a two-area power system subject to inter-area oscillations is stabilized with a proportional damping controller that uses wide-area measurement feedback. This compensator uses two signals that are subject to different and independent latencies. This paper analyzes the two area system as a Multiple Input Multiple Output (MIMO) system and studies the effect that independent time delays have on the stability of the system. A root-locus approach, where latencies are estimated using a Padé approximation is used towards that goal. Results show that larger time delays can destabilize the system if they occur simultaneously in both measurements. This work also studies the impact that communication latencies have on the sensitivity of the system with respect to load disturbances. This analysis was performed by assessing variations in the largest peak of the maximum singular value. Time domain simulations are also presented to corroborate the results of the root-locus approach and the sensitivity analysis.

The remainder of this paper is organized as follows. Section II introduces the two-area power system and its describing equations. Section III analyses the effect that communication latencies and the proportional gain of the controller have on the stability of the system and its ability to reject load disturbances. Section IV presents time domain simulations and finally Section V outlines the conclusions of the work.

II. Power System Model

The plant model used in this research is a linearized version of a two-area power system and is shown in Fig. 1 [10]. The model has an undamped inter-area oscillation of 0.24 Hz. Each area of the system is composed of a turbine and a governor, represented by $C_i(s)$, and a block representing the dynamics of the inertia and load, denoted $G_i(s)$. The two areas are linked together by the *synchronizing torque*, a term called κ, whose value depends on the power transfer between the areas and the equivalent impedance between them. The synchronizing torque determines the ability of the system to keep in synchronism after a disturbance and tends to decrease with greater power transfer. Lower κ values mean the system has less stability robustness to disturbances. The inputs ΔP_{L1} and ΔP_{L2} represent disturbances (imbalances in the load and/or generation) in each area of the system. The system also has one High Voltage Direct Current (HVDC) line linking

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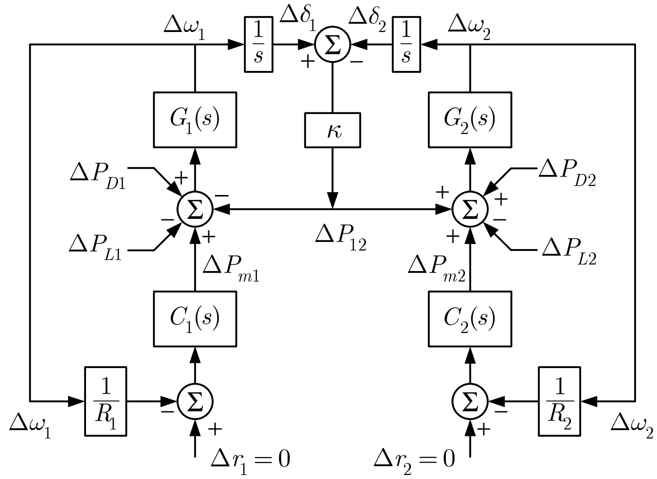

Fig. 1. Linear model of a two-area power system (adapted from [10]).

the two areas that is represented by the two power injections: ΔP_{D1} and ΔP_{D2} in Area 1 and Area 2 respectively. Because of the nature of an HVDC link, in which power drained in one end is the opposite of the power injected at the other end (neglecting losses), ΔP_{D1} is always the negative of ΔP_{D2}. In this work a proportional control of these HVDC injections is used to stabilize the system. The control law for each injection is

$$P_{D1}(t) = -K_d(f_1(t-T_1) - f_2(t-T_2)) \tag{1}$$

$$P_{D2}(t) = -P_{D1}(t) = K_d(f_1(t-T_1) - f_2(t-T_2)) \tag{2}$$

Notice that the controller uses two signals that are subject to two different communication latencies: $f_1(t)$ which is the frequency in area 1 and is subject to a delay of T_1 and $f_2(t)$ which is the frequency in area 2 with a latency of T_2. A controller of these characteristics has been proposed for the WECC system [11].

A. Frequency Domain Description

The system in Fig. 1 can also be represented by the schematic diagram shown in Fig. 2, with $r = 0$ and the load changes in both areas represented as a vector $\Delta P_L = [\Delta P_{L1}, \Delta P_{L2}]^{\mathrm{T}}$ of input disturbances. The output is defined as the vector of frequencies at each area $\Delta\omega = [\Delta\omega_1, \Delta\omega_2]^{\mathrm{T}}$. In this case, the two dimensional controller is represented as a 2×2 matrix $\mathbf{K}$ whose components are

$$K_{11} = -K_d e^{-T_1 s} \qquad K_{12} = K_d e^{-T_2 s}$$
$$K_{21} = K_d e^{-T_1 s} \qquad K_{22} = -K_d e^{-T_2 s}$$

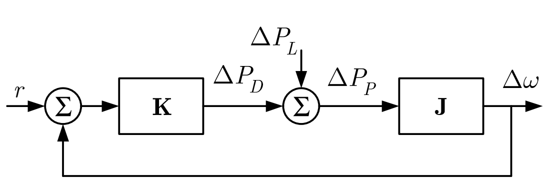

Fig. 2. Control loop schematic of the system in Fig. 1.

and the plant to be controlled, that is the two-area power, is expressed by a matrix noted $\mathbf{J}$ whose components are expressed as

$$J_{11} = \frac{-L_{22}G_1}{L_{12}L_{21} - L_{22}L_{11}} \quad J_{12} = \frac{-L_{12}G_2}{L_{12}L_{21} - L_{22}L_{11}} \tag{3}$$

$$J_{21} = \frac{-L_{21}G_1}{L_{12}L_{21} - L_{22}L_{11}} \quad J_{22} = \frac{-L_{11}G_2}{L_{12}L_{21} - L_{22}L_{11}} \tag{4}$$

where

$$L_{11} = 1 + \frac{G_1 T}{s} + \frac{G_1 C_1}{R_1} \qquad L_{12} = \frac{G_1 T}{s} \tag{5}$$

$$L_{21} = \frac{G_2 T}{s} \qquad L_{22} = 1 + \frac{G_2 T}{s} + \frac{G_2 C_2}{R_2} \tag{6}$$

The plant and controller relationships are described with the equations $\Delta P_D = \mathbf{K}\Delta\omega$ and $\Delta\omega = \mathbf{J}\Delta P_P$. The input-output relationship of the MIMO system can then be expressed as

$$\Delta\omega = (\mathbf{I} - \mathbf{JK})^{-1}\mathbf{J}\Delta P_L \tag{7}$$

B. Input Sensitivity Analysis

The system in Fig. 2, with $r = 0$ can also be used to analyze the effect that disturbances ΔP_L have on the input of the plant ΔP_P. In particular, it can be shown that the relationship between the input to the plant, ΔP_P, and the input disturbances, ΔP_L, is

$$\Delta P_P = (\mathbf{I} - \mathbf{KJ})^{-1}\Delta P_L \tag{8}$$

where $(\mathbf{I} - \mathbf{KJ})^{-1} = S_i$ is defined as the input sensitivity [12]. To reduce the effects of disturbances into the plant, it is desired that the gain from ΔP_L to ΔP_P, represented by S_i, to be small for all conditions. The worst-case scenario of gain is represented by the maximum singular value $\overline{\sigma}(Si)$ of the input sensitivity [12]. For a given stabilizing controller $K(s)$, this work assesses the effects that communication latencies have on the maximum singular value of S_i.

III. Effects of Different Time Delays on System Stability and Input Sensitivity

This section presents the effect that variations in the control proportional gain (K_d), and the latencies in the frequency measurements (T_1, T_2) have on the stability of the inter-area oscillations of the system. It then outlines how the sensitivity to disturbances is affected by the control gains as well as the individual communication latencies. Although latencies in practice are likely to be subject to randomness and jitter, the impact of stochastic time delays is beyond the scope of this paper.

A. Inter-area mode variation as local and remote signal time delay increases

The system in Fig. 1 can be described using a state space representation provided that the latencies (represented by exponential functions) are approximated by states using a Padé approximation. The stability of the system is then defined by the eigenvalues of the state matrix. In this paper, a Padé approximation of order 4 was used to represent latencies in the state space domain[1].

In the absence of a controller ($K_d = 0$) the two-area system in Fig. 1 is unstable and has an inter-area mode located at $0.06848 \pm j1.48$. Considering the case where there are no communication latencies in the system, i.e. $T_1 = T_2 = 0$, then the system becomes symmetric and increases in K_d stabilize it. The blue line (circle marker) in Fig. 3 (a) shows this effect when K_d is increased from 0 to 10. Fig. 3 (a) shows the variations in the inter-area mode of the system as K_d is increased from 0 to 10 for different values of latencies when the latencies for both frequency measurements are symmetrical. Fig. 3 (b) in turn shows variations in the inter-area mode of the system for similar increases of K_d for different values in time delays in either one of the measurements (the other one has no latency i.e. is assumed to be zero). These results show for a smaller delay of 0.1 s the difference between delay in one signal vs. delay in both signals (green lines in Fig. 3 (a) and (b)) is minimal. Delays in both signals push the inter-area mode slightly to the left half plane, and the oscillation increases. When delay is increased, results show improved stability when it occurs in only one of the measurements (compared to both).

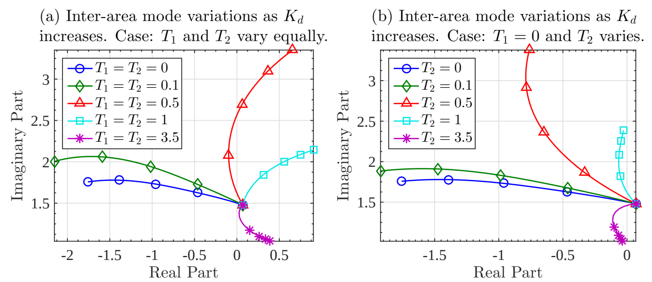

Fig. 3. Inter-area mode variations as K_d increases.

To further explore the effects of individual time delays in the stability of the system, root-loci analysis is performed for the inter-area mode as time delays are increased for several proportional constants, K_d. Figs. 4 (a)-(d) show variations in the inter-area mode as latencies T_1 and T_2 are increased from 0 to 3.5 seconds for values of K_d = 0.25, 1, 2.5 and 5, respectively. To help visualize the results in Fig. 4, the damping of the inter-area mode for the same cases is shown in Fig. 5.

Results in Figs. 4 and 5 show that increasing communication latencies in any of the signals independently tends to destabilize the system for all the different values of K_d considered. When both measurement signals experience time delays, the overall performance of the controller is decreased.

B. Variations in the maximum singular value of S_i as local and remote signal time delay increase

The effect that load disturbances have on the plant is determined by the matrix of transfer functions (input sensitivity) S_i in relationship (8). The gain that S_i gives to the disturbances depends on the input themselves and their direction

[1]Approximations of different orders were tried and the results were comparable

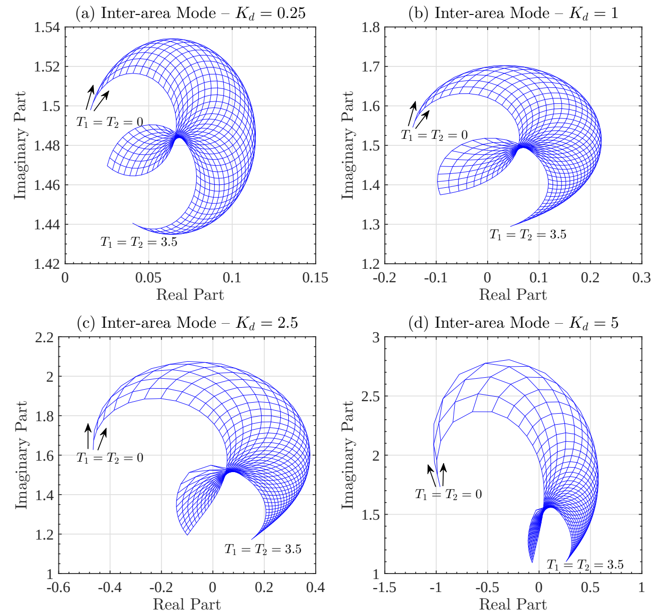

Fig. 4. Inter-area mode variations as T_1 and T_2 are independently increased for different values of the proportional constant K_d.

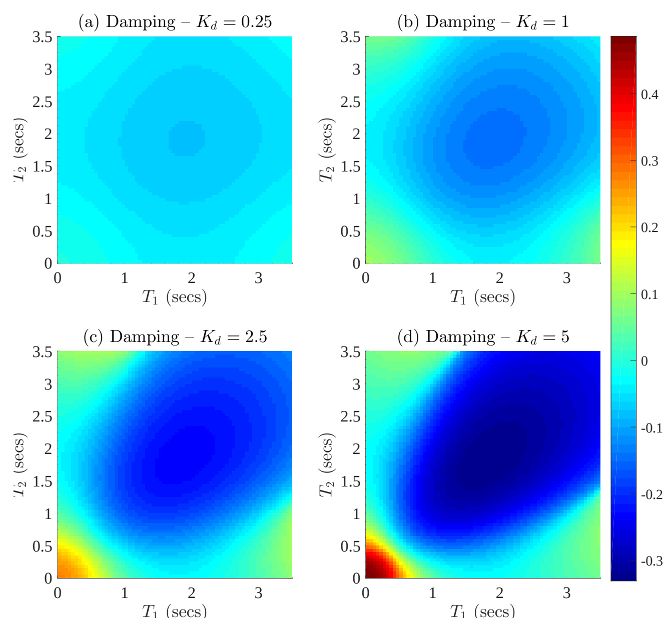

Fig. 5. Variations in the damping ratio of the inter-area mode as the system experiences independent increases in T_1 and T_2 for different values of the proportional constant K_d.

(i.e. the coupling between the two inputs). The maximum singular value of S_i determines the maximum possible gain that these transfer functions can provide and is dependent on the frequency. This section presents the impact that the communication latencies T_1, T_2 and the proportional gain K_d have on the largest peak of the maximum singular value of S_i as a proxy to analyze the impact they have on the ability of the system to reject input disturbances.

Fig. 6 (a) shows how the largest peak of $\overline{\sigma}(S_i)$, referred to as $M_p(S_i)$, varies as a function of K_d for different cases of communication latencies when they are symmetric[2]. The blue line (circle marker) represents the case where there are no delays associated with the measurements and shows that increasing K_d do not considerably affect $M_p(S_i)$. When time delays are associated with the measurements it is observed that initial increases in K_d will represent increments in M_p and that increases in the symmetric latencies in general represent a larger M_p. Fig. 6 (b) shows how M_p is affected by increments in K_d for cases when the communication latencies associated with the measurements are asymmetric. In particular, only one of the measurements has latency while the other has no delay. Comparing the results in Fig. 6 (a) with those in Fig. 6 (b), it is observed that larger time delays (T_1 and T_2) occurring on both measurements indicate higher M_p than if they occurred only in one of them.

Fig. 7 shows how the largest peak of the maximum singular value of of the input sensitivity $M_p(S_i)$ change when the delays in the measurements T_1 and T_2 are increased from 0 to 3.5 seconds. The analysis was performed for K_d of values: 0.25, 1, 2.5 and 5 and is presented in Figs. 7 (a)-(d) respectively. These results indicate that increases in the latencies of the measurements make the system more sensitive to load disturbances. This increase in sensitivity is also more pronounced for larger values of the proportional gain K_d.

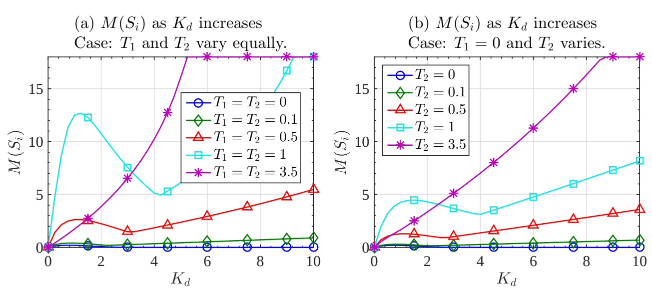

Fig. 6. Variations in the largest peak of the maximum singular value of S_i with increments in K_d. Left: when the two time delays are kept the same. Right: when only one of the latencies is changed while the other remains at zero.

IV. Time Domain Simulations

In this section, time domain simulations of the linearized system in Fig. 1 are performed to confirm the results presented in Section III. The disturbance considered in the simulations is a step input of magnitude 0.02 pu, occurred at 1 second, in the local input signal ΔP_{L1}. The other input of the system ΔP_{L2} remains unchanged (i.e. a value of zero during the simulation).

Figs. 8 (a)-(d) show the difference in generator speeds ($\Delta\omega_{21}(t)$ in pu) for different values of proportional constant K_d. Fig. 8 (a) shows that the system is unstable when no control is applied (i.e. $K_d = 0$). Fig. 8 (b) shows that a small K_d constant may start providing some stability. Figs. 8 (c)-(d) show that for larger values of K_d the system is stabilized when none of the measurements experience communication latencies. These figures also show that when delays start to appear for both measurements symmetrically, the stability

[2]The peak was limited to 18 so the different results can be observed at the same scale.

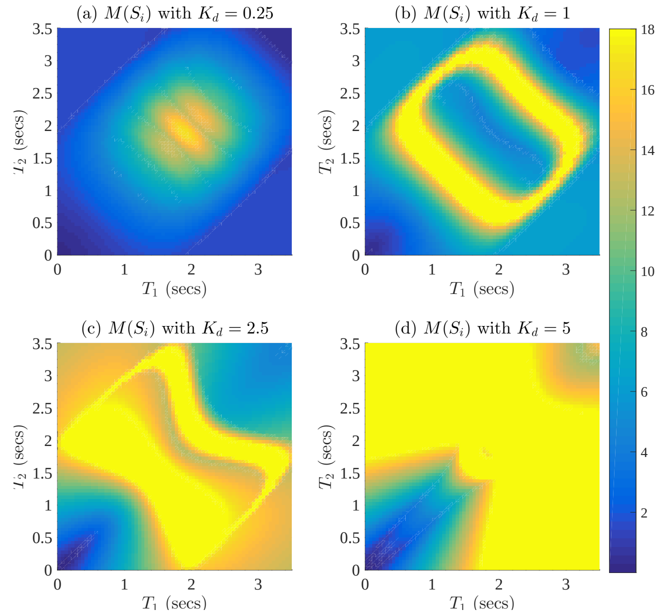

Fig. 7. Largest peak of the maximum singular value of the input sensitivity function S_i as T_1 and T_2 are independently increased for different values of the proportional constant K_d.

of the system is rapidly lost. Note that these results are in accordance with those presented in Figs. 3(a).

Fig. 9 shows the difference in generator speeds ($\Delta\omega_{21}(t)$) when there is asymmetry in the latencies of the measurement signals when $K_d = 1$. Fig. 10 shows a similar set of simulations, when $K_d = 2.5$. The results in Figs. 9 and 10 show that for smaller time delays in the frequency measurements both values of K_d stabilize the system with higher values yielding more damping. However these results also show that for higher latencies, especially when they occur in both measurements, increases in K_d have a destabilizing effect on the system. In those cases, a higher value of K_d results in a higher destabilizing effect from the latencies. These results validate those presented in Figs. 3(a), 4 and 5.

V. Conclusions and Future Work

A simple wide-area proportional controller to an HVDC link is used in this work to stabilize a two-area system. The controller uses frequency signals from each of the areas to modulate the HVDC power transfer. This paper studies how asymmetries in the latencies of these frequency signals affect both the stability and robustness to disturbances of the system. A linear version of the system is analyzed as a MIMO system consisting of a matrix of transfer functions with time delays represented as exponential functions. A state space representation is derived using a Padé approximation and eigenanalysis is used to determine the stability characteristics of the system. A load disturbance sensitivity analysis is presented based on the variations that the largest peak of the singular value has with respect to the communication latencies.

The results of mode analysis show that increasing the proportional gain stabilizes the system when the delays are small. However, when both delays increase simultaneously, this effect

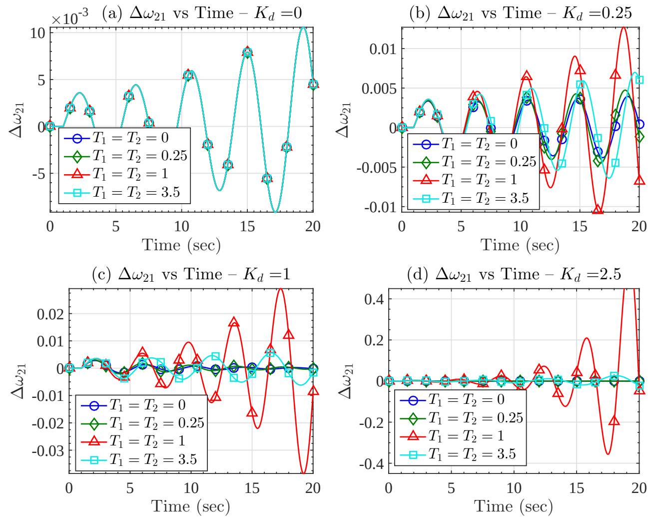

Fig. 8. Time simulation of the linear system in Fig. 1 for different proportional gain K_d values. (a) when $K_d = 0$ the system has no controller and hence latencies do not have any effect on it. (b) $K_d = 0.25$. (c) $K_d = 1$. (d) $K_d = 2.5$.

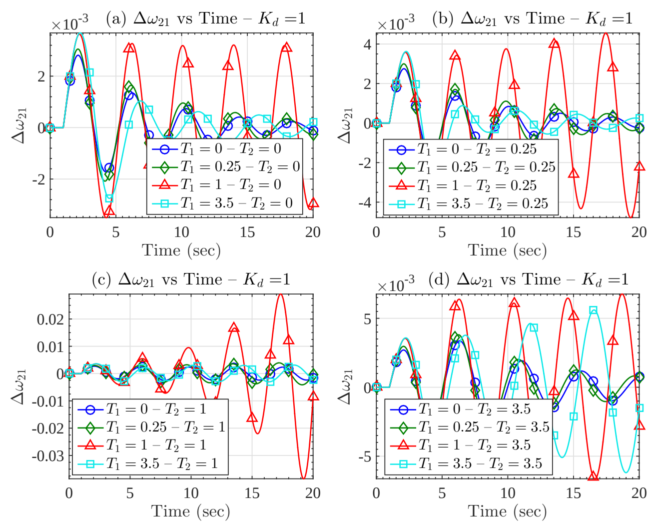

Fig. 9. Time simulation of the linear system for different cases of communication latencies when $K_d = 1$.

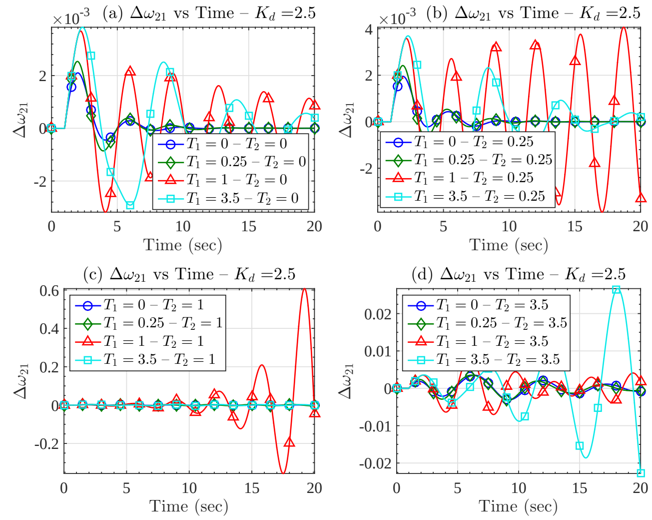

Fig. 10. Time simulation of the linear system for different cases of communication latencies when $K_d = 2.5$.

is reversed. It is worth noting that individual increases in either of the latencies have a lower destabilizing effect than if the delay occurs in both measurements. The results of the sensitivity analysis show that increments in the communication delays increase largest peak of the singular value which makes the system less able to reject load disturbances. Finally, time domain simulations were conducted and their results show a strong agreement with the root-locus approach.

Because communication latencies are random in nature, future work will include analyzing how this stochasticity affects the stability and robustness of the system.

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