Delayed-Input Power System Stabilizer using Supplementary Remote Signals

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Abstract: The design of a local $H_\infty$-based power system stabilizer controller, using wide area or global signals as additional measuring information considering time delay is presented in this paper. The wide area signals are taken from suitable remote network locations where the oscillations are well observable. A long time delay introduced by remote signal transmission and processing in wide area measurement system (WAMS), may be harmful to system stability and may degrade system robustness. Three methods for dealing with the effects of time delay are presented in this paper. To provide robust behavior, $H_\infty$ control theory together with an algebraic Riccati equation approach has been applied to design the proposed controller. The simulation results show that the designed controller contributes significantly to the damping of inter-area oscillations and the enhancement of small-signal stability in the presence of uncertainty in time delay under a wide range of system operating conditions.

Keywords: inter-area oscillations, PSS, remote signals, WAMS, time delay, robust controller, $H_\infty$ control.

1. INTRODUCTION

Weakly damped low frequency inter-area oscillations, inherent to large interconnected power systems during transient conditions, are not only dangerous for the reliability and performance of such systems but also for the quality of the supplied energy. With the heavier power transfers ahead, the damping of these oscillations will decrease unless new lines are built (construction of new lines is restricted by environmental and cost factors) or other heavy and expensive high-voltage equipment such as series-compensation is added to the grid’s substations. Therefore, the achievement of maximum available transfer capability as well as a high level of power quality and security requires the need for a better coordinated protection and system stability control which leads to damping improvement.

It is found that if remote signals from one or more distant locations of the power system are applied to the controller design, the system dynamic performance can be enhanced for a better damping of inter-area oscillations (Snyder et al., 2000). The recent advances in wide area measurement (WAM) technologies using phasor measurement units (PMUs) can deliver synchronous control signals at high speed (Heydt et al., 2001). PMUs are deployed at strategic locations on the grid to obtain a coherent picture of the entire network in real time (Heydt et al., 2001). Global positioning system (GPS) technology ensures proper time synchronization among several global signals (Heydt et al., 2001). The measured global signals are then transmitted via modern telecommunication equipment to the controllers.

An experimental research (Naduvathparambil et al., 2002) has shown that time delays in wide area control systems caused by different communication links are different but all the delays are more than 100 ms. In the case of satellite link, the propagation delay could be as high as above 700 ms. There could be a larger delay when a large number of signals are to be routed and signals from different areas are waiting for synchronization. Such large time delays can invalidate many controllers that work well in no delayed-input systems and even cause disaster accidents (Kolmanovskii et al., 1999). The design of a controller, therefore, must take into account this delay in order to provide a controller that is robust, not only for the range of operating conditions desired, but also for the uncertainty in delay (Snyder et al., 2000).

The design of a local power system stabilizer (PSS) controller using remote signals as supplementary inputs without considering time delay is presented in (Hashmani and Erlich, 2008). This paper considers a problem of improving the performance of local conventional PSS by using instantaneous measurements from remote locations of the grid considering time delay. Three methods for dealing with the effects of time delay are presented in this paper. First, time delay compensation method using lead/lag compensation along with gain scheduling for compensating effects of constant delay is presented. In the second method, Pade approximation approach is used to model time delay. The time delay model is then merged into delay-free power system model to obtain the delayed power system model. Delay compensation and Pade approximation methods deal with constant delays and are not robust regarding time delays. Time delay uncertainty is, therefore, taken into account using linear fractional transformation (LFT) method.

$H_\infty$-based robust control technique is used to design proposed PSS controller. Digital simulation studies on a two-machine power system are conducted to investigate the effectiveness of the proposed controller during system disturbances.
The rest of the paper is organized as follows: In Section 2, design of time delay compensator, Padé approximation method to describe time delay, power system model with time delay and LFT method to describe uncertainty in time delay are presented. In Section 3, the proposed robust $H_{\infty}$-based PSS controller is designed. In Section 4, a dynamic model of the two-machine system used in this study is discussed. The digital simulation results are presented in Section 5 and the conclusions are discussed in Section 6.

2. TIME DELAY IN POWER SYSTEMS

2.1 Design of Delay Compensator

Delay compensator consisting of lead/lag and gain modules is designed to diminish the effect of time delay. The effect of time delay on an oscillatory mode ($\sigma + j \omega$) is to introduce damping with respect to angular frequency $\omega$ and gain amplification with respect to damping $\sigma$. The effect might derive eigenvalues of system matrix to undesirable places on complex plane and can make power system unstable. Phase lead due to delay $\tau$ is $\phi = \omega \tau$ while the gain amplification $\gamma_c$ due to delay $\tau$ is $\gamma_c = e^{-\alpha \tau}$.

Delay in time could be compensated in phase provided by lead/lag compensation block along with gain scheduling as shown in Fig. 1. In Fig. 1, output signals $Y_{1df}$ of the delay-free system plant $P(s)$ are the remote input signals of the PSS controller. The time delay, therefore, occurs only in $Y_{1df}$. In order to compensate the effect of this time delay on the system performance, $Y_{1df}$ are added to the delay compensator $H_c(s)$. The output signals $Y_{id}$ of delay compensator, therefore, represents the delayed remote input signals of the PSS controller $C(s)$. The output signal $Y_{2df}$ of delay-free system plant is the local input signal to the PSS controller and is, therefore, without time delay.

![Fig. 1. Framework of wide area damping control](image)

Transfer function of delay compensator is given as:

$$H_c(s) = K[(1 + s T_1)/(1 + s T_2)]$$

where, $T_1 = 1/(\omega \sqrt{\alpha})$, $T_2 = \alpha T_1$,

$$\alpha = [1 - \sin(\phi/2)]/[1 + \sin(\phi/2)]$$

Phase lead ($\phi = \omega \tau$) provided by delay compensator balances the phase lag due to delay $\tau$. Gain $K$ provided by delay compensator reduces the gain amplification $\gamma_c$ due to delay $\tau$.

2.2 Padé Approximation Method for Constant Delay

Time delay $\tau$ in a signal can be expressed as $e^{\alpha \tau}$. By using Padé approximation (Cabannes H., 1976), $e^{\alpha \tau}$ is expressed as (Wu Hongxia et al., 2002):

$$\begin{align*}
\dot{x}_d(t) &= A_d x_d(t) + B_d u_d(t) \\
y_{id}(t) &= C_d x_d(t) + D_d u_d(t)
\end{align*}$$

Delay-free power system plant can be expressed as follows:

$$\begin{align*}
\dot{x}_d(t) &= A_d x_d(t) + B_d u_d(t) \\
y_{id}(t) &= C_d x_d(t) + D_d u_d(t)
\end{align*}$$

where,

$$y_{id}(t) = \begin{bmatrix} y_{1id} & y_{2df} \end{bmatrix}^T, C_d = \begin{bmatrix} C_{1df} & C_{2df} \end{bmatrix}^T,$$

$$D_d = \begin{bmatrix} D_{1df} & D_{2df} \end{bmatrix}^T.$$
2.3 LFT Method for Time Delay Uncertainty

In LFT method, a time delay uncertainty can be described by an LFT (Zhou and Doyle, 1998). Delay-free power system model is then cascaded with uncertain time delay model to obtain the uncertain delayed power system model as shown in Fig. 3. Controller design based on LFT can keep the system stable over the delay uncertainty range.

By using 1st-order Padé approximation, delay $e^{-\tau s}$ in a signal can be represented by the following equations (Wu Hongxia, et al., 2002):

$$
\dot{x}_d(t) = -\frac{2}{\tau} x_d(t) + u_d(t)
$$  \hspace{1cm} (10)

$$
y_d(t) = \frac{4}{\tau} x_d(t) - u_d(t)
$$  \hspace{1cm} (11)

By using (10) and (11), the block diagram of time delay $e^{-\tau s}$ can be drawn as shown in Fig. 4.

Parameter $\tau$ is not known exactly. However, it can be assumed that its value is within certain known interval, i.e.,

$$
\tau = \tau(1 + p_\tau \delta_\tau)
$$  \hspace{1cm} (12)

where, $\tau$ is the nominal value of $\tau$, $p_\tau$ and $\delta_\tau$ represent the possible (relative) perturbations on $\tau$. $p_\tau$ represents the boundary values within which the value of $\tau$ lies. Perturbation $\delta_\tau$ is assumed to be unknown but lie in the interval [-1, 1].

The term $1/\tau$ in Fig. 4 can be represented as an LFT in $\delta_\tau$, i.e., as a feedback interconnection of a constant matrix and an uncertainty matrix $\delta_\tau$. as follows:

$$
\frac{1}{\tau} = \frac{1}{\tau(1 + p_\tau \delta_\tau)} = \frac{1}{\tau} - \frac{p_\tau}{\tau} \delta_\tau(1 + p_\tau \delta_\tau)^{-1} = F_\tau(M_{\tau \delta_\tau})
$$  \hspace{1cm} (13)

where,

$$
M_{\tau \delta_\tau} = \begin{bmatrix} p_\tau & 1 \\ -\frac{1}{\tau} & \frac{1}{\tau} \end{bmatrix}
$$  \hspace{1cm} (14)

Equation (13) together with (14) represents LFT of the term $1/\tau$. The term $1/\tau$ in Fig. 4 is, therefore, replaced by its LFT with an associated matrix $M_{\tau \delta_\tau}$, as shown in Fig. 5.

Fig. 5. Block diagram representation of time delay $e^{-\tau s}$

The block diagram shown in Fig. 5, representing delay $e^{-\tau s}$ can be described by the following equations:

$$
\begin{bmatrix} y_N \\ \dot{x}_d \\ y_d \\ u_N \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \begin{bmatrix} u_N \\ 4x_d - 2x_d \end{bmatrix}
$$  \hspace{1cm} (15)

$$
\begin{bmatrix} y_N \\ y_d \end{bmatrix} = \begin{bmatrix} \alpha_{11} & \alpha_{12} \\ \alpha_{21} & \alpha_{22} \end{bmatrix} \begin{bmatrix} u_N \\ x_d \end{bmatrix}
$$  \hspace{1cm} (16)

By substituting values of $M_{11}$, $M_{12}$, $M_{21}$, $M_{22}$ from (14) into (15) and then writing (15) and (17) in matrix form, gives:

$$
\begin{bmatrix} \dot{x}_d \\ y_N \\ y_d \end{bmatrix} = \begin{bmatrix} -\frac{2}{\tau} & \frac{4}{\tau} \\ -2 & 4 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} x_d \\ u_N \end{bmatrix}
$$  \hspace{1cm} (18)

3. $H_{\infty}$ CONTROLLER DESIGN FOR POWER SYSTEMS

3.1 Problem Formulation

The overall extended system equations for the linear, time-invariant, continuous-time composite system, composed of $N$ subsystems, are written as follows (Hashmani and Erlich, 2008):

$$
\dot{x}(t) = A_d x(t) + B_d w(t)
$$  \hspace{1cm} (19)

$$
z(t) = C_d x(t) + D_d w(t)
$$  \hspace{1cm} (20)

where, $x(t) = [x^T(t) \ x_0^T(t)]^T$, $A_d = \tilde{A} + \tilde{B}_2 K_d \tilde{C}_2$, $B_d = \tilde{B}_1 + \tilde{B}_2 K_d \tilde{C}_2$, $C_d = \tilde{C}_1 + \tilde{D}_2 K_d \tilde{C}_2$, $D_d = \tilde{D}_1 + \tilde{D}_2 K_d \tilde{D}_2$

3.2 Controller design using Riccati-based approach

Designing an $H_{\infty}$ controller for the system is equivalent to that of finding matrix $K_d$, in (19) and (20), that satisfies an $H_{\infty}$ norm bound condition on closed loop transfer functions $T_{rz}(s) = C_d(sI - A_d)^{-1}B_d$ from disturbance $w(t)$ to controlled outputs $z(t)$ in Fig. 6, i.e., $\|T_{rz}(s)\|_{\infty} < \gamma$ (for a given scalar
constant \( \gamma > 0 \). Moreover, \( T_{\text{ex}}(s) \) must be stable (Gahinet and Apkarian, 1994). An algebraic Riccati equation (ARE) approach (Doyle et al., 1989) can be applied to establish the existence of control strategy.

The base operating conditions are taken from (Hashmani and Erlich, 2008). Values can be found in (Hashmani and Erlich, 2008).

Moreover, for all simulation studies as well as for the PSS design, the structure of the \( n_i \)-th order PSS controller in a multimachine power system (Hashmani and Erlich, 2008) is considered.

With this controller \( H_{\alpha} \) disturbance attenuation is \( \gamma = 0.0101 \).

4.5 Controller Design for Uncertain Delay System

By considering that the uncertainty in the time delay ranges from 0 ms to 700 ms, (12) can be written as:

\[
\tau = \tau + \bar{\tau} p \delta, \quad \bar{\tau} = 0.35 + 0.35 \delta, \quad \delta \in [-1,1].
\]

The design procedure of Section 3.2 is used to design the controller. Matlab Robust Control Tool box is used for the design purpose.

4.2 Reduced-Order Controller Design for Delay-Free System

By considering that the time delay in the remote input signal \( P_{\text{el}}(t) \) of the PSS controller is 700 ms and following the procedure described in Section 2.1, delay compensator designed is:

\[
H_{\alpha} = \frac{1.1714 + s + 0.004}{1 + s + 0.0501}.
\]

With this controller \( H_{\alpha} \) disturbance attenuation is \( \gamma = 0.0102 \).

4.3 Design of Delay Compensator for Constant Delay System

By considering that the time delay is 700 ms and using 1st-order Padé approximation, the constant matrices \( A_d, B_d, C_d, D_d \) for the time delay model of (1) and (2) can be obtained as:

\[
A_d = \frac{2}{\tau}, \quad B_d = 1, \quad C_d = \frac{4}{\tau}, \quad D_d = -1.
\]

For reducing the order of controller, the procedure given in (Hashmani and Erlich, 2008) is followed. The reduced-order \( H_{\alpha} \)-based PSS controller, thus, obtained is:

\[
\begin{bmatrix}
4.613 (1 + s) 14.71 \\
5.2983 (1 + s) 11.85
\end{bmatrix}
\begin{bmatrix}
1 + s & 28.59 \\
1 + s & 28.59
\end{bmatrix}
\]

The \( H_{\alpha} \) disturbance attenuation is \( \gamma = 0.0102 \).

4.4 Controller Design for Constant Delay System

By considering that the time delay is 700 ms and using 1st-order Padé approximation, the constant matrices \( A_d, B_d, C_d, D_d \) for the time delay model of (1) and (2) can be obtained as:

\[
A_d = \frac{2}{\tau}, \quad B_d = 1, \quad C_d = \frac{4}{\tau}, \quad D_d = -1.
\]

For reducing the order of controller, the procedure given in (Hashmani and Erlich, 2008) is followed. The reduced-order \( H_{\alpha} \)-based PSS controller, thus, obtained is:

\[
\begin{bmatrix}
4.613 (1 + s) 14.71 \\
5.2983 (1 + s) 11.85
\end{bmatrix}
\begin{bmatrix}
1 + s & 28.59 \\
1 + s & 28.59
\end{bmatrix}
\]

The \( H_{\alpha} \) disturbance attenuation is \( \gamma = 0.0102 \).
By substituting the values of \( \tau \) and \( p_e \) into (22), the constant matrices \( A_d, B_d, C_d, D_d \) for the uncertain time delay model of (10) and (11), can be obtained as follows:

\[
A_d = -5.7142, B_d = 11.4284, C_d = 1, D_d = -1
\]

Reduced-order \( H_{\infty} \)-based PSS controller, thus, obtained is:

\[
\begin{bmatrix}
32.191 + s0.031 \\
1 + s3.264
\end{bmatrix} \quad \begin{bmatrix}
25.4561 + s0.47 \\
1 + s3.264
\end{bmatrix}
\]

The \( H_{\infty} \) disturbance attenuation is \( \gamma = 0.6228. \)

5. SIMULATION RESULTS

In order to simulate the system behaviour under large disturbance conditions, a balanced three-phase fault is applied at bus 3 as shown in Fig. 7. The fault sequence of the three-phase fault used in these simulations is as follows:

Stage 1: The system is in pre-fault steady-state.
Stage 2: A three-phase fault occurs at \( t = 1.0 \) s.
Stage 3: The fault is cleared at \( t = 1.2 \) s.
Stage 4: The system is in a post-fault state.

5.1 Delay Compensator Case

Fig. 8 shows the behaviours of deviation of \( P_e(t) \) with \( H_{\infty} \)-based PSS controller designed without considering delay in its remote input signal. Fig. 8 indicates that the response of deviation of \( P_e(t) \), with \( H_{\infty} \)-based PSS controller designed without considering delay, is better damped when no delay is included in the remote input signal of the controller during the simulation but becomes oscillatory when a constant delay of 700 ms is included in the remote input signal during the simulation. Fig. 8 also indicates that for a constant delay of 700 ms, is better damped as compared to that with \( H_{\infty} \)-based PSS controller designed without considering delay.

5.2 Pade Approximation Method for Constant Delay Case

Fig. 9 shows the behaviours of deviation of \( P_e(t) \) with \( H_{\infty} \)-based PSS controllers designed without considering time delay and with considering constant time delay of 700 ms in their remote input signals. Fig. 9 indicates that for a constant delay of 700 ms included in the remote input signal during the simulation, the response of deviation of \( P_e(t) \), with \( H_{\infty} \)-based PSS controller redesigned considering constant delay of 700 ms, is better damped as compared to that with \( H_{\infty} \)-based PSS controller designed without considering delay.

5.3 LFT Method for Time Delay Uncertainty Case

Fig. 10 shows the behaviours of deviation of \( P_e(t) \) with \( H_{\infty} \)-based PSS controllers designed without considering time delay and with \( H_{\infty} \) controller redesigned considering delay uncertainty.
delay and with considering uncertainty in the time delay in its remote input signal. Fig. 10 indicates that for a time delay of 700 ms included in the remote input signal during the simulation, the response of deviation of $P_{e}(t)$, with the $H_{\infty}$-based PSS controller redesigned considering uncertainty in time delay, is better damped as compared to that with the $H_{\infty}$-based PSS controller designed without considering delay.

5.4 Robustness of Controller Regarding Time Delay

To further assess effectiveness of the proposed approach regarding robustness, transient performance indices are computed for different time delays. Transient performance index for electrical power output of the generator, following a three-phase short-circuit of 200 ms duration at bus 3 in Fig. 7, is computed using the following equation:

$$I = \int_{0}^{\infty} \left| P_{e}(t) - P_{e0}(t) \right| \, dt$$

(21)

For comparison purpose, this index is normalized to the index for the mean value of delay range considered in the delay uncertainty case:

$$I_{N} = \frac{I_{DD}}{I_{MD}}$$

(22)

where $I_{DD}$ is transient performance index for different time delays and $I_{MD}$ is transient performance index for the mean value of delay range considered in the delay uncertainty case.

Fig. 11. Normalized transient performance index $I_{N}$ for electrical power generated

The normalized transient performance indices, for the electrical power output of the generator, for the time delays ranging from 0 to 700 ms, with the proposed $H_{\infty}$-based PSS controller, designed considering uncertainty in delay in its remote input signal and with the $H_{\infty}$-based PSS controller, designed without considering delay in its remote input signal are shown in Fig. 11. It can be seen from the Fig. 11 that the normalized transient performance indices for the proposed $H_{\infty}$-based PSS controller, are more near to unity, for the range of delays for which the controller is designed, as compared to those for the $H_{\infty}$-based PSS controller designed without considering delay in its remote input signal. This clearly indicates that, for different delays, the transient responses of the generator with the proposed $H_{\infty}$-based PSS controller, designed considering delay uncertainty, are well damped as compared to those with the $H_{\infty}$-based PSS controller, designed without considering delay. This indicates that, the system behavior exhibits robustness with the proposed controller for the range of delays for which the controller is designed. This shows that the proposed $H_{\infty}$-based PSS controller, designed considering delay uncertainty, is more robust regarding time delay uncertainty as compared to the $H_{\infty}$-based PSS controller, designed without considering delay.

6. CONCLUSIONS

An $H_{\infty}$-based dynamic output feedback PSS controller design, using both local and remote signals as the feedback input signals, considering time delay in the remote signals, is developed. Three methods for dealing with the effects of time delay are presented. The nonlinear simulations results have shown that the proposed controller is effective and robust in suppressing system oscillations not only for a wide range of operating conditions but also for the uncertainty in delay under large disturbances in the system studied.

REFERENCES


