Wide-area Power System Damping Control Coordination Based on Particle Swarm Optimization with Time Delay Considered

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Abstract. To ensure satisfactory dynamic performance of controllers in time-delayed power systems, a WAMS-based control strategy is investigated in the presence of output feedback delay. An integrated approach based on Pade approximation and particle swarm optimization (PSO) is employed for parameter configuration of PSS. The coordination configuration scheme of power system controllers is achieved by a series of stability constraints at the aim of maximizing the minimum damping ratio of inter-area mode of power system. The validity of this derived PSS is verified on a prototype power system. The findings demonstrate that the proposed approach for control design could damp the inter-area oscillation and enhance the small-signal stability.

1. Introduction

The low frequency oscillation of interconnected system brings challenges to the inter-area power dispatch and transmission [1-2] and the utilization of remote signals is of vital significance to damp low frequency oscillation and boost dynamic performance. However, the centralized controller entails inputs that may arrive after a certain communication delay in WAMS. Because of its destructive influence on small-signal stability, system robustness and voltage oscillation of power grids [3-4], time delay can be hardly ignored in wide area control.

Various approaches have been taken to overcome the limitations of transmission delay in WAMS, such as robust control theory [5], fuzzy control [6] and model predictive control (MPC) [7]. In contrast to the wealth of studies tackling the time-delayed problem with classical control theories, there has been less research adopting intelligent algorithm, which is an optimization method with superior random searching strategy and faster convergence speed. In the light of this, the aim of this study is to explore a combined control strategy with intelligent algorithm and equivalent transformation.

In this paper, a combinatorial approach of power system stabilizer (PSS) design is adopted in this work to address the damping control problem with regard to time-delayed power systems. Firstly, by employing Pade rational polynomials to approximate the value of time delay, the augmented state matrix of power systems is formulated. Secondly, the coordination configuration scheme of power system controllers is achieved by a series of stability constraints and PSO, and an eigenvalue-based objective function to increase the system damping is proposed. Lastly, the validity of this method is verified on a two-area four-machine system.

2. Model of time delayed power system

The dynamic model of power system is usually illustrated by a set of differential algebraic equations, which can be linearized at an equilibrium point in the form of state space as follows:
\[
\begin{align*}
\dot{x}_p(t) &= A_p x_p(t) + B_p u_p(t) \\
y(t) &= C_p x_p(t) + D_p u_p(t)
\end{align*}
\] (1)

With local and wide-area supplementary damping controller installed on the power system (1) shown in Fig.1, transmission delay is introduced.

Therefore, the time-delayed power system is
\[
\dot{x}(t) = A_c x(t) + A_d x(t - \tau)
\] (2)

where \( A_c \) and \( A_d \) are matrix containing both system and control parameters.

3 Controller design

The aim of this paper is to design supplementary controllers to damp low frequency oscillation considering the multiple time delays so as to improve power system security. As shown in Fig.2, the general model of PSS consists of an amplifier, a reset element, a phase compensator and a limiter. In PSS feedback loop, the input signal is converted to a supplementary excitation signal.

In this study, PSS is introduced as supplementary control (both local and wide-area control) to damp the power system. The local PSS could be expressed as
\[
G_l(s) = K_l \left( \frac{T_s}{1 + T_s} \right) \left( \frac{1 + T_{il}s}{1 + T_{il}s} \right) \left( \frac{1 + T_{is}s}{1 + T_{is}s} \right) (3)
\]

and the wide-area PSS could be expressed as
\[
G_w(s) = K_w \left( \frac{T_s}{1 + T_s} \right) \left( \frac{1 + T_{iw}s}{1 + T_{iw}s} \right) \left( \frac{1 + T_{is}s}{1 + T_{is}s} \right) (4)
\]
The goal in this study is to find the parameters of these two PSSs.

3.1 Pade approximation. Time delay, expressed as the exponential function $e^{-\tau s}$, could be also equivalently formulated as

$$\begin{cases}
\dot{x}_r(t) = A_r x_r(t) + B_r y_w(t) \\
y_w(t) = C_r x_r(t) + D_r y_w(t)
\end{cases}$$

By using Pade approximation, the time delay module could be transferred into state space form, which is no longer difficult to deal with.

Consider the power system (1) with local control, wide area control and time delay module, the time-delayed power system with supplementary control is

$$\dot{x}_{all}(t) = A_{all} x_{all}(t)$$

where $x_{all}(t) = [x_p(t) \ x_i(t) \ x_w(t) \ x_r(t)]$.

3.2 Parameter configuration with PSO. Both the local and wide-area supplementary controllers are to be designed. For the best performance of intelligent algorithm, some parameters of PSS given. Generally, the $T_{il}, T_{lw}$ of PSS are unknown and $T_{2i}, T_{2w}$ are set to a specific value.

The design of PSS is therefore defined as an optimized problem with unequal constraints below

$$\begin{align*}
\max & \quad J \\
\text{s.t.} & \quad K_{min} < K_i, K_w < K_{max} \\
& \quad T_{ilmin} < T_{il} < T_{ilmax} \\
& \quad T_{1wmin} < T_{lw} < T_{1wmax} \\
& \quad \text{eig}(A_{all}) < 0
\end{align*}$$

$$\xi = -\xi_i \sqrt{\sigma_i^2 + \omega_i^2}$$.

Accordingly, the object function could be rewritten as $f = \min f_{\text{fitness}}$ where fitness degree function $f_{\text{fitness}}(x)$ is split as $f_{\text{fitness}}(x) = f(x) + g(x)$, the objective function $f(x)$ is denoted as $f(x) = -\max J$,

while the penalty function $g(x)$ is defined as $g(x) = \sum_{i=1}^{n_p} N_p \cdot \text{real}(x_i)$.

3.3 Procedure of control design. The procedure of control design could be summarized as follows.

Input the data of power system and initialize the particle and speed of PSO and set the limit.
Calculate the augment state matrix of the time-delayed power system and its eigenvalue.
Check whether the constraints are satisfied.
Calculate the fitness value of each particle and rank them.
Continue iteration until the allowable maximum number of iteration.

4. Results

The two-area four-machine system with data mainly inspired from [1] and adopted for this study to test the proposed method. The modal analysis with results in Table I illustrates three electromechanical modes with two local modes (mode 1 and 2) and one inter area mode (mode 3).
Table 1. Electromechanical Modes of Power System

| Mode | Eigenvalue       | Damping ratio | Participant machines |
|------|------------------|---------------|----------------------|
| 1    | -0.1030 ± 6.2610i| 0.0164        | G1, G2               |
| 2    | -0.5192 ± 6.8519i| 0.0755        | G3, G4               |
| 3    | 0.1209 ± 3.6288i | -0.0333       | G1-G4                |

As damping ratio of mode 2 and 3 are insufficient, 2 PSSs, namely PSS1 (as local PSS) and PSS2 (as remote PSS) are installed on the power system to damp the local mode inter-area mode. The PSSs here adopt angular velocity type PSS.

By calculating the controllability and observability of mode 1 and mode 3, we choose $\Delta \omega_2$ of G2 as the feedback signal to PSS1 on G1, and $\Delta \omega_4$ of G4 as the feedback signal to PSS2 on G2.

The goal is to optimize the $T_d, T_m, K_f, K_w$ of the two PSSs. In this study, fifth order Padé approximation is used to replace the time delay module.

The given parameters of PSSs are: $T_d = T_m = 0.05s$, $T = 10s$, $\tau = 0.2s$. In PSO, the number of particle $N = 40$, learning factor $c_1 = c_2 = 2$, maximum allowable iteration $M = 50$, dimension $D = 4$, penalty factor $N_p = 10$. The initial value of weight $w_0 = 0.5$, the allowable $F_0 = 0.5$.

According to the design procedure in Section III, the parameters of two PSSs could be designed as:

$$G_{pss1}(s) = 13.7712 \frac{10s}{10s + 1} \left(1 + \frac{0.01s}{1 + 0.05s}\right)^2$$

$$G_{pss2}(s) = 3.3523 \frac{10s}{10s + 1} \left(1 + \frac{0.01s}{1 + 0.05s}\right)^2$$

and the value of fitness function in iteration process is illustrated in Fig.3. As can be seen, the final value of fitness function is -0.0633, which indicates that the inter-area mode is damped effectively.

An eigenvalue analysis of the closed-loop system was carried out to examine the performance of the designed controllers where the time delay module is replaced by Padé approximation. Effect of these derived controllers is illustrated in Table II.

Table 2. Electromechanical Modes with Controller

| Mode | Time delay | Eigenvalue       | Damping ratio |
|------|------------|------------------|---------------|
| 1    | With 0.1s delay | -0.4305 ± 6.7849i | 0.0633        |
| 2    | With 0.2s delay | -1.0599 ± 6.9328i | 0.1511        |
| 3    | With 0.1s delay | -0.4176 ± 6.7772i | 0.0615        |
| 2    | With 0.2s delay | -1.0430 ± 6.9092i | 0.1493        |
| 3    | With 0.1s delay | -0.2659 ± 3.4857i | 0.0761        |
The results in Table II reveals that the damping ratio of mode 3 improves to 0.0519 with 0.1s time delay and 0.0761 with 0.2s time delay. Besides, both mode 1 and mode 2 are damped in the presence of the controllers. This indicates that the proposed method is effectively enhance the power system stability and reduce the negative effect of time delay.

With different wide-area signal delays considered, the system response to a small disturbance and large disturbance at the reference voltage of excitation on G2 is shown in Fig. 4 and Fig. 5. The power system is unstable without supplementary control. With the proposed PSSs, the power system could be damped effectively. Compare the curve of 0.2s time delay with 0.1s time delay, the former time delayed power system is much more stable than the latter.

In conclusion, the damping performance of the designed controllers is therefore considered effective to enhance the damping ratio and boost the small-signal stability of time-delay system against negative or low damping modes.

Figure 4. System response with different wide-area signal delays (small disturbance)

![Figure 4](image_url)

Figure 5. System response with different wide-area signal delays (large disturbance)

![Figure 5](image_url)

5. Conclusion

This paper proposed a WAMS-based PSS design strategy with output feedback delay considered to ensure satisfactory dynamic performance of controllers in power systems. An integrated approach based on Padé approximation and PSO is employed for parameter configuration of PSS. By employing state space expression of fifth order Padé rational polynomials to approximate the value of time delay, the time delay link element could be transformed into a linear element and an augmented state space model.
of power system is formulated. The validity of this derived PSS is verified on a two-area four-machine power system. Through eigenvalue analysis and time domain simulation, the proposed approach could damp the inter-area oscillation effectively and enhance power system stability.

References

[1] Kundur P, Balu N J and Lauby M G 1994 Power system stability and control, vol.7. New York: McGraw-hill.
[2] Zhu F, Zhao H, Liu Z and Kou H 2007 The influence of large power grid interconnected on power system dynamic stability. Proceedings of the CSEE, vol. 27.1-7.
[3] Jia H, Chen J and Yu X 2006 Impact of time delay on power system small signal stability. Automation of Electric Power Systems, vol. 18. no.3 pp389-391.
[4] Jia H., Xie X and YuX 2006 Power system small signal stability region with time delay considered. Automation of Electric Power Systems vol. 30 no.21 pp.1-5.
[5] JiangQ, Zhang P and Cao Y 2006 Wide-area FACTS damping control in consideration of feedback signals’ time delays. Proceedings of the CSEE vol. 44no.7 pp.82-88.
[6] Mokhtari M, Aminifar F, Nazarpour D and Golshannavaz S 2013 Wide-area power oscillation damping with a fuzzy controller compensating the continuous communication delays. IEEE Transactions on Power Systems vol. 28 pp1997-2005.
[7] Azad S P, Iravani R and Tate J E 2013 Damping inter-area oscillations based on a model predictive control (MPC) HVDC supplementary controller. IEEE Transactions on Power Systems vol. 28 pp3174-83.