Comparative Research on the Influence of Signal Selection on Delay Margin in Interarea Oscillation Damping Control

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***Abstract* — Conventional signal selection method for damping controller is based on non-delay linear control system model and neglects the influence of signal transmission delay on signal selection. Feedback signal selected by the conventional method may not be applicable for interarea oscillation damping control when signal is delay for a certain period. To overcome this disadvantage, a new power system damping control model with considering signal transmission delay is proposed. Then, a novel influence analysis approach of signal selection on delay margin is presented. By using this novel approach, the implicit relationship of signal selection and delay margin can be obtained and appropriate feedback signal for damping controller can be determined such that damping controller can effectively damp interarea oscillations in the scenarios of signal transmission delay. Simulation tests on four-generator two-area power system verify the effectiveness of the proposed approach in signal selection of damping controller in the scenarios of signal transmission delay.**

Keywords - Interarea Oscillation; Power System Stabilizer; Flexible AC Transmission Systems; Unified Power Flow Controller

I. INTRODUCTION

Interarea low frequency oscillation is a severe threat to power system stability operation [1]. The oscillation that can not be damped quickly and timely would cause power flow in transmission line to fluctuate or a generator group to oscillate against another generator group, and then lead to power system instability or even collapse [2]. Until now, damping interarea oscillation is still a big challenge for power system operators [3]. According to different damping control mechanisms, two damping control methods are adopted in electrical industry. The first damping control method is wide area damping controller (WADC), which has similar controller structure as power system stabilizer (PSS) and can provide damping control function by adjusting generator's exciter. The second damping control method is supplementary damping controller (SDC), which provides additional damping controller function by utilizing flexible ac transmission systems (FACTS) devices such as SVC, TCSC, and UPFC [4]. For example, SDC based SVC can simultaneously implement two functions: supplementary damping control function and main function of bus voltage adjustment [5]. Similarly, UPFC with SDC not only control active power and reactive power over transmission line [6],[7], but also damp interarea oscillations by its SDC [8]. Both of these two damping control methods have been widely used in practical power system.

For interarea oscillations to be damped, damping controller including WADC and SDC should select feedback signal with the maximum mode observability as its input [9]. Conventional signal selection method, e.g., residue method, is based on non-delay linear control system model which neglects the influence of signal transmission delay on signal selection. Feedback signal selected by the conventional method may not be applicable for interarea oscillation damping control when signal is delay for a certain period. In fact, signal transmission delay in practical power system is usually in the range from several milliseconds to several hundred milliseconds or more [10]. The delay can not be neglected in feedback signal selection in the design of damping controller [11, 12].

Therefore, the influence of signal selection in damping controller design in the scenarios of signal transmission delay is analyzed in this paper. The contributions of this paper includes: (a) a new power system damping control model with delay is proposed. The new proposed model is superior to conventional damping control model based on non-delay linear control system since it considers the influence of signal transmission delay in the process of modeling. (b) a novel influence analysis approach of signal selection on delay margin is presented in detail. By using this novel approach, appropriate feedback signal for damping controller can be selected on the tradeoff between required signal transmission delay and expected damping control requirement.

II. INFLUENCE ANALYSIS APPROACH OF SIGNAL SELECTION ON DELAY MARGIN

A. Disadvantages of Conventional Signal Selection Method

Since conventional damping control model is based on non-delay linear control system, residue method, as a conventional signal selection method for damping controller, is usually to identify appropriate input signal of damping controller for obtaining better damping control performance [9]. Residue method generally includes three steps: (a) selecting feedback signal with the maximum mode observability corresponding to interarea oscillation to be damped as damping controller input; (b) determining lead-lag time constants of damping controller, T_1, T_2, T_3, and T_4, by residue compensation; (c) identify damping controller gain, k_{sdc}, by root locus on the objective of better damping ratio or damping factor. It is clear that residue method is a kind of frequency-domain method and neglects the influence of signal transmission delay. Damping controller designed by residue method would deteriorate its damping performance when signal measured at remote location is delivered to control location during a period of delay, or even cause power system instability if the delay is beyond delay margin that the system can endure. Signal selected by residue method may not be the best signal for damping controller when signal is delayed for a certain period since, in the scenarios of signal transmission delay, the selection of damping controller input signal would influence the effectiveness of interarea oscillation damping control. Because conventional signal selection method based on residue method is not applicable in this case, there is need to investigate the influence of signal selection on delay margin in interarea oscillation damping control. The research is of great value because it can provide guidance for signal selection in the design of damping controller in the scenarios of signal transmission delay.

B. Damping Control Model with Signal Transmission Delay

In order to select proper signal for damping controller in the scenarios of signal transmission delay, the first step is to construct power system damping control model considering signal transmission delay. The new model is based on time delay control system instead of non-delay linear control system used in conventional signal selection method.

Differential-algebraic equations of the open-loop power system are given below:

$$\begin{aligned} \dot{\boldsymbol{x}}_0 &= f(\boldsymbol{x}_0, \boldsymbol{w}_0, \boldsymbol{u}_0) \\ 0 &= g(\boldsymbol{x}_0, \boldsymbol{w}_0, \boldsymbol{u}_0) \\ \boldsymbol{y}_0 &= h(\boldsymbol{x}_0, \boldsymbol{w}_0, \boldsymbol{u}_0) \end{aligned} \tag{1}$$

where $\boldsymbol{x}_0$, $\boldsymbol{w}_0$, $\boldsymbol{u}_0$, and $\boldsymbol{y}_0$ are state, algebraic, control, and output variables of the open-loop power system, respectively. Since interarea oscillation damping control has two modes: generator exciter based WADC and FACTS based SDC, it is noted that the open-loop power system should include generator exciter and FACTS devices, but not include WADC and SDC.

Linearizing these equations at a certain operating point yields:

$$\begin{aligned} \dot{\boldsymbol{x}}_0(t) &= \boldsymbol{A}_0\boldsymbol{x}_0(t) + \boldsymbol{B}_0\boldsymbol{u}_0(t) \\ \boldsymbol{y}_0(t) &= \boldsymbol{C}_0\boldsymbol{x}_0(t) \end{aligned} \tag{2}$$

where $\boldsymbol{A}_0$, $\boldsymbol{B}_0$ and $\boldsymbol{C}_0$ are state, input, and output matrices of the linearized open-loop power system, respectively. Damping controllers, WADC and SDC, are used to damp interarea oscillations. Their mathematical model is given below by state space model:

$$\begin{aligned} \dot{\boldsymbol{x}}_c(t) &= \boldsymbol{A}_c\boldsymbol{x}_c(t) + \boldsymbol{B}_c\boldsymbol{u}_c(t) \\ \boldsymbol{y}_c(t) &= \boldsymbol{C}_c\boldsymbol{x}_c(t) + \boldsymbol{D}_c\boldsymbol{u}_c(t) \end{aligned} \tag{3}$$

where $\boldsymbol{x}_c$, $\boldsymbol{y}_c$, and $\boldsymbol{u}_c$ are state, output, and input variables of WADC and SDC, $\boldsymbol{A}_c$, $\boldsymbol{B}_c$, $\boldsymbol{C}_c$, and $\boldsymbol{D}_c$ are state matrix, input matrix, output matrix, and direct transmission matrix of the controllers, respectively. Output variable of power system or feedback signal, $\boldsymbol{y}_0$, is generally a single signal coming from a remote measurement location, e.g., active power flow and current magnitude, or is a combined signal retrieving from multiple measurement locations, e.g., voltage phase angle different over transmission line. When signal transmission delay $d(t)$ is considered, input variable of damping controller, $\boldsymbol{u}_c$, and output variable of power system, $\boldsymbol{y}_0$, comply with: $\boldsymbol{u}_c(t) = \boldsymbol{y}_0(t - d(t))$, $\boldsymbol{u}_0(t) = \boldsymbol{y}_c(t)$. Combining (2) and (3) with considering signal transmission delay $d(t)$ yields the following power system damping control model:

$$\begin{aligned} &\dot{\boldsymbol{x}}(t) = \boldsymbol{A}\boldsymbol{x}(t) + \boldsymbol{A_d}\boldsymbol{x}(t - d(t)),\ d(t) \le \tau, \dot{d}(t) \le \mu \\ &\boldsymbol{x} = (\boldsymbol{x}_0, \boldsymbol{x_c})^T \end{aligned} \tag{4}$$

where τ and μ are upper bound and variation rate of the delay $d(t)$, $\boldsymbol{A} = \begin{pmatrix} \boldsymbol{A}_0 & \boldsymbol{B}_0\boldsymbol{C_c} \\ 0 & \boldsymbol{A_c} \end{pmatrix}$, $\boldsymbol{A}_d = \begin{pmatrix} \boldsymbol{B}_0\boldsymbol{D}_c\boldsymbol{C}_0 & 0 \\ \boldsymbol{B_c}\boldsymbol{C}_0 & 0 \end{pmatrix}$.

It is known from (4) that power system damping control model is based on linear time delay control system, which develops conventional damping control theory based on linear non-delay control system and lays a foundation for damping control signal selection in the scenarios of signal transmission delay.

C. The Relationship of Signal Selection and Delay Margin

Based on the above analysis, the relationship of signal selection and delay margin can be obtained by the following procedures:

(a) select candidate feedback signal $\boldsymbol{y}_0$ by residue method. These candidate signals have the relatively larger mode observability corresponding to interarea oscillation to be damped.

(b) for candidate feedback signal $\boldsymbol{y}_0$, construct the model (2) of the open-loop power system. It is noted that the model (2) is different for each candidate feedback signal.

(c) for candidate feedback signal $\boldsymbol{y}_0$, determine lead-lag time constants of damping controller, T_1, T_2, T_3, and T_4, by residue compensation.

(d) for candidate feedback signal $\boldsymbol{y}_0$, construct damping controller model (3) by given damping control gain, k_{sdc}, and known lead-lag time constants of damping controller, T_1, T_2, T_3, and T_4. It is noted that time-domain equation of damping controller formed by $\boldsymbol{A}_c$, $\boldsymbol{B}_c$, $\boldsymbol{C}_c$, and $\boldsymbol{D}_c$, is equivalent to frequency-domain equation of damping controller determined by k_{sdc}, T_1, T_2, T_3, and T_4.

(e) for candidate feedback signal $\boldsymbol{y}_0$, construct power system damping control model (4) by combining (2) and (3) which are obtained in the step (b) and (d), respectively.

(f) for candidate feedback signal $\boldsymbol{y}_0$ and given damping control gain k_{sdc}, calculate delay margin τ of power system damping control model (4) by the following theorem [13].

Theorem 1: given scalars τ>0 and μ, power system (4) is stable if there exist matrices $\boldsymbol{R}=\boldsymbol{R}^T>0$, $\boldsymbol{S}=\boldsymbol{S}^T\geq 0$, and $\boldsymbol{T}=\boldsymbol{T}^T>0$, $\boldsymbol{X}=\begin{bmatrix}\boldsymbol{X}_{11} & \boldsymbol{X}_{12}\\ \boldsymbol{X}_{12}^T & \boldsymbol{X}_{22}\end{bmatrix}\geq 0$, and any appropriately dimensioned matrixes $\boldsymbol{N}_1$ and $\boldsymbol{N}_2$ such that the following linear matrix inequalities (LMIs) hold.

$$\begin{bmatrix}\boldsymbol{X}_{11} & \boldsymbol{X}_{12} & \boldsymbol{N}_1\\ \boldsymbol{X}_{12}^T & \boldsymbol{X}_{22} & \boldsymbol{N}_2\\ \boldsymbol{N}_1^T & \boldsymbol{N}_2^T & \boldsymbol{T}\end{bmatrix}\geq 0 \quad (5)$$

$$\begin{bmatrix}\boldsymbol{\Phi}_{11} & \boldsymbol{\Phi}_{12} & \tau\boldsymbol{A}^T\boldsymbol{T}\\ \boldsymbol{\Phi}_{12}^T & \boldsymbol{\Phi}_{22} & \tau\boldsymbol{A}_d^T\boldsymbol{T}\\ \tau\boldsymbol{T}_3\boldsymbol{A} & \tau\boldsymbol{T}\boldsymbol{A}_d & -\tau\boldsymbol{T}\end{bmatrix}<0 \quad (6)$$

where

$$\boldsymbol{\Phi}_{11}=\boldsymbol{R}\boldsymbol{A}+\boldsymbol{A}^T\boldsymbol{R}+\boldsymbol{N}_1+\boldsymbol{N}_1^T+\boldsymbol{S}+\tau\boldsymbol{X}_{11}$$
$$\boldsymbol{\Phi}_{12}=\boldsymbol{R}\boldsymbol{A}_d-\boldsymbol{N}_1+\boldsymbol{N}_2^T+\tau\boldsymbol{X}_{12}$$
$$\boldsymbol{\Phi}_{22}=-\boldsymbol{N}_2-\boldsymbol{N}_2^T-(1-\mu)\boldsymbol{S}+\tau\boldsymbol{X}_{22}$$

(g) repeat steps (b)-(f) for each candidate feedback signal $\boldsymbol{y}_0$, and eventually obtain the implicit relationship of signal selection and delay margin for all candidate feedback signal. That is to say, the relationship table of candidate feedback signal $\boldsymbol{y}_0$, delay margin τ, and damping control gain k_{sdc} is formed, which can be used to analyze the influence of signal selection on delay margin in interarea oscillation damping control in the scenarios of signal transmission delay.

(h) select appropriate feedback signal $\boldsymbol{y}_0$ among all candidate feedback signals on the tradeoff between required signal transmission delay and expected damping control requirement.

D. Model Order Reduction for Large-Scale Power System

For large-scale power system, state variable of the open-loop power system, $\boldsymbol{x}_0$, is of high dimension. The dimension of system state variable $\boldsymbol{x}_0$ in model (2) is the sum of dimensions of electrical devices including generators, exciters, governors, power system stabilizers, FACTS, etc. When the number of these electrical devices increases, the dimension of system state variable $\boldsymbol{x}_0$ increases dramatically with the time of the number of these electrical devices. In practical power system, the dimension of model (2) is hundreds of, or even thousands of orders. In order to accelerate calculation speed of delay margin τ by theorem 1, the dimension of model (2) should be reduced. Generally, there are three model reduction methods: Schur model reduction, Hankel optimal model reduction, and balanced truncation order reduction. The principle of model order reduction is that the reduced-order model (2) has the similar frequency response as the full-order model (2) in the range of interarea oscillation frequency. After the dimension of model (2) is reduced, combining reduced-order model (2) and damping controller model (3) still yields power system damping control model (4) which has lower orders. Then, the influence of signal selection on delay margin in interarea oscillation damping control in the scenarios of signal transmission delay can be analyzed by implementing the similar procedures as steps (a)-(h).

III. NUMERICAL STUDIES

In the above sections, the influence analysis approach of signal selection on delay margin in interarea oscillation damping control is proposed. In this section, the proposed approach is tested on the four-generator two-area power system [1], a classical test system of low frequency oscillation. The system has two local oscillations and one interarea oscillation. SDC based on UPFC is applied to damp interarea oscillation. SDC has five parameters to be determined: k_{sdc}, T_1, T_2, T_3, and T_4. UPFC is installed at tie line between the first area and the second area. In the test, the following SDC input signal is chosen: 1) current magnitude $I_{6\text{-}7}$ in the transmission line 6-7; 2) active power $P_{7\text{-}8}$ in the transmission line 7-8. The full order model of the system is reduced as the 7th order equivalent model by Schur model reduction method. To simplify SDC design, T_1 is assumed to be equal to T_3, and T_2 equal to T_4 in SDC model (3).

In order to analyze the influence of signal selection on delay margin in interarea oscillation damping control, the relation of signal selection and delay margin is calculated by the above procedures (a)-(h). The calculation results are shown in Table I. In the table, f and ζ denote frequency and damping ratio of the dominant oscillation mode without considering delay influence, respectively. To compare the influence of SDC input signal on damping performance under the same damping controller gain, k_{sdc} is set equally for signals $I_{6\text{-}7}$ and $P_{7\text{-}8}$ in Table I.

It is clear from Table I that for signals I6-7 and P7-8, with the increase of damping controller gain k_{sdc}, damping ratio ζ increases but delay margin τ decreases correspondingly. Besides, it is also clear that for the same damping controller gain k_{sdc}, delay margin τ decreases with the increase of delay variation rate μ. By comparing computation results in Table I, it is found that damping ratio for P7-8 is slightly lower than that for $I_{6\text{-}7}$, while delay margin τ for $P_{7\text{-}8}$ is much greater than that for $I_{6\text{-}7}$. Therefore, $P_{7\text{-}8}$ is better signal than $I_{6\text{-}7}$ for interarea oscillation damping control in the scenarios of signal transmission delay. For example, in the context that signal transmission delay is 0.35ms, it is clear from Table I that SDC with input signal $I_{6\text{-}7}$ can not effectively damp interarea oscillation in the scenarios of signal transmission delay since the maximum delay margin obtained by signal $I_{6\text{-}7}$ is 0.3456ms, but SDC with input signal $P_{7\text{-}8}$ can.

TABLE I. DELAY MARGİN τ UNDER DİFFERENT DELAY VARİATİON RATE μ FOR SİGNALS $I_{6\text{-}7}$ AND $P_{7\text{-}8}$

Signal	k_{sdc}	μ=0	μ=0.2	μ=0.4	f (Hz)	ζ
$I_{6\text{-}7}$	**1.0**	**0.3456**	**0.3301**	**0.3225**	**0.5341**	**0.2749**
	1.1	0.2774	0.2262	0.2354	0.5292	0.2822
	1.2	0.2549	0.2102	0.2073	0.5245	0.2887
	1.3	0.2350	0.1972	0.1797	0.5202	0.2942
	1.4	0.2158	0.1769	0.1596	0.5161	0.2991
$P_{7\text{-}8}$	1.0	0.4447	0.4011	0.4252	0.5682	0.2485
	1.1	0.4160	0.3966	0.4005	0.5652	0.2575
	1.2	0.4012	0.3200	0.3496	0.5622	0.2661
	1.3	0.3763	0.3415	0.3528	0.5592	0.2744
	1.4	0.3621	0.3083	0.3162	0.5560	0.2824

IV. CONCLUSION

This paper presents the influence analysis approach of signal selection on delay margin in interarea oscillation damping control. By the proposed approach, appropriate input signal of damping controller can be obtained such that damping controller can effectively damp interarea oscillations in the scenarios of signal transmission delay. Compared with conventional signal selection method based on residue method, the proposed approach overcomes disadvantages of residue method and gives the implicit relationship of signal selection and delay margin. Simulation tests verify the effectiveness of the proposed approach in the selection of damping controller input signal in the scenarios of signal transmission delay.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

ACKNOWLEDGMENT

This work is supported by National Natural Science Foundation of China (No.51007042 and 51577136), Science & Technology Foundation of Hunan Provincial Education Department, China (No.14C0782), and Fund of Mintong Shiji Technology Co. Ltd.

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