AN APPROACH FOR TUNING OF POWER SYSTEM STABILIZERS BASED ON THE WIDE AREA PHASOR MEASUREMENT

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Abstract - This paper presents a method for tuning of power system stabilizers (PSS) for damping low-frequency oscillations in a multi-machine power system based on the wide area phasor measurement. The authors have developed a method for detecting inter-area low-frequency modes from the measured small oscillation associated with the load fluctuation by approximating oscillations as a coupled vibration model. An approach based on the approximate model has been also investigated for tuning PSS parameters and the assessment of the effectiveness of tuning control in the real power system. Some numerical analyses demonstrate the effectiveness of the method by using phasor dynamical data obtained by a power system simulation package.

Keywords - power system control, power system stabilizer, phasor measurement, low-frequency oscillation, coupled vibration

1 INTRODUCTION

INTERCONNECTIONS in a power system are intended to improve the reliability and the economical efficiency. On the other hand, it occasionally causes the inter-area low-frequency oscillation with poor damping characteristics [1, 2]. Therefore, many kinds of methods for designing the power system stabilizer (PSS) have been developed to damp inter-area oscillations as well as local oscillations. It has been investigated in the literatures that the PSS design based on the Prony method [3], the identification of low-order state-space models of power systems by using multi-input multi-output procedures [4], and the low-order identification technique coupled with a robust controller design technique based on genetic algorithm [5].

Recently, real-time monitoring of power systems based on the wide area phasor measurement attracts power system engineers for the state estimation and system protections especially under a deregulated environment with complex power contracts [6]. Proper grasp of the present state with flexible wide area control should become key issues to keep the power system stability properly. The authors have developed the wide area measurement system in Japan by using Phasor Measurement Units (PMUs) synchronized by the Global Positioning System (GPS) signal so far. The GPS furnishes a common-access timing pulse, which is accurate to within 1 microsecond at any location on the earth. Therefore, observed phasors measured at multiple locations are synchronized with high accuracy. In this project a method to identify major swing modes is proposed by modeling measured oscillations as a coupled vibration model, in which voltage phasors at measurement sites in the normal operating condition are used. Small oscillation data associated with the load fluctuation are used to model a coupled vibration model to consider the mode interaction. Oscillation modes, especially the inter-area low-frequency mode with poor damping, can be detected from the measured data [7]. As a result, detected unstable modes can be damped effectively by controlling the power system, for example, by tuning PSS parameters based on the measurement data.

In this paper, a method for tuning of PSSs combined with the wide area phasor measurement is proposed. The derived coupled vibration model based on the measurement represents power system oscillations, which can be used to tune PSS parameters and to assess the effectiveness of PSS tuning in the real power system. The advantage of this method is that steady state phasor fluctuations are available to assess the effect of the tuned control. In other words, a large disturbance like a line fault is not necessary since the stability of major modes can be investigated directly by using eigenvalues of the coupled model. The identification process does not require the information on input to the system for perturbation, while ordinary methods based on the system identification require both input and output to the system [3, 4, 5]. In this paper, some numerical analyses demonstrate the effectiveness of the proposed method by using phasor dynamical data obtained by a power system simulation package.

2 MODAL ANALYSIS WITH A COUPLED VIBRATION MODEL

The power swing equations of generators in an n-machine system are represented by [8]

$$\begin{aligned} M_i\dot{\omega}_i &= -D_i(\omega_i - 1) + P_{mi} - P_{ei} \\ \dot{\delta}_i &= \omega_r(\omega_i - 1) \end{aligned} \qquad (1)$$

where, $i = 1, 2, \cdots, n$, ω is the angular velocity, δ is the rotor angle, M is the inertia constant, D is the damping coefficient, P_m is the mechanical input to the generator, P_e is the electrical output, and $\omega_r = 120\pi$ is the rated angular velocity in a 60 Hz system.

In a multi-machine power system multiple swing modes exist and interact with each other. For example, in a longitudinally interconnected power system like the Western Japan 60 Hz system, two inter-area modes associated with power oscillations tend to be dominant and interact with each other. One of the modes is associated with the oscillation between both end generators, the other is associated with the oscillation between both end and the middle generators. These oscillation characteristics can be explained by right eigenvectors and the participation factor described in APPENDIX. Note that the following method is applicable to any other systems than a longitudinal system in cases where characteristic oscillations are observed.

Here, a coupled vibration model is considered to represent the interaction of two modes. These modes are assumed to oscillate with keeping the dynamics of power swing equations (1). The first vibration model corresponds to the most dominant mode, while the other corresponds to the second dominant mode. Two observation sites near generators which significantly participate in these two modes are selected, while another site is used as the reference of the phase angle. The dynamics of the model is represented by the polynomial approximation of the phase angle and the angular velocity:

$$\dot{x}_1 = \frac{\omega_r}{M_1}(-D_1(\omega_1 - 1) + P_{m1} - P_{e1}) \approx f_1(x_1, x_2, x_3, x_4) \quad (2)$$

$$\dot{x}_2 = x_1 \quad (3)$$

$$\dot{x}_3 = \frac{\omega_r}{M_2}(-D_2(\omega_2 - 1) + P_{m2} - P_{e2}) \approx f_2(x_1, x_2, x_3, x_4) \quad (4)$$

$$\dot{x}_4 = x_3. \quad (5)$$

Here, f_1 and f_2 are assumed to consist of linear terms:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} a_1 & a_2 & a_3 & a_4 \\ 1 & 0 & 0 & 0 \\ b_1 & b_2 & b_3 & b_4 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} \quad (6)$$

where $x_1 = \dot{\delta}_1 - \dot{\delta}_s$, $x_2 = \delta_1 - \delta_s - (\delta_{1e} - \delta_{se})$, $x_3 = \dot{\delta}_2 - \dot{\delta}_s$, and $x_4 = \delta_2 - \delta_s - (\delta_{2e} - \delta_{se})$. Subscripts 1 and 2 denote numbers of selected sites, the subscript s denotes the reference site, and the subscript e denotes the initial value of the phase angle. The coefficients a_i and b_i ($i = 1 \sim 4$) can be evaluated by applying the least squares method to time series data sets of x_j ($j = 1 \sim 4$) obtained by the wide area phasor measurement. Oscillation characteristics are investigated directly by using this model since eigenvalues of the coefficient matrix represent the damping and frequency of two oscillatory modes. If necessary, this model can be extended to the case expressed in more than two dominant modes, that is, by increasing state variables and choosing the corresponding sites according to the number of the dominant modes.

On the other hand, the oscillation data obtained by the wide area measurement are the phase angle and include many frequency components associated with inter-area low-frequency oscillations as well as local oscillations and many noises. Here, discrete Wavelet analysis is applied to extract oscillations including dominant two modes from measurement data. Inter-area oscillations with frequencies between 0.2 and 0.8 Hz can be extracted, while local modes with frequencies higher than 1.0 Hz and many noises with high frequencies can be eliminated by using Wavelet transformation. Thus, data sets of phase difference x_2 and x_4 are provided. On the other hand, the angular velocity x_1 and x_3 can be calculated by differentiating x_2 and x_4, respectively.

3 AN APPROACH FOR TUNING OF POWER SYSTEM STABILIZERS

Identified inter-area low-frequency modes by using the above method have occasionally poor damping characteristics. Therefore, these modes have to be damped by controlling the power system. The use of power system stabilizer (PSS) is effective to stabilize inter-area modes. In this section, an approach for tuning of PSSs based on the phasor measurement is proposed.

3.1 A coupled vibration model including the effect of power system stabilizers

The model of object k-th PSS is

$$G_{\mathrm{PSS}k}(s) = \frac{K_k}{1 + sT_0} \cdot \frac{sT_w}{1 + sT_w} \cdot \frac{1 + sT_{1k}}{1 + sT_{2k}} \cdot \frac{1 + sT_{3k}}{1 + sT_{4k}} \quad (7)$$

which describes the real one consisting of a two-stage lead-lag compensation. Here, $T_{1k}, \cdots, T_{4k}$ are time constants, K_k is a gain, T_0 is time lag for the signal detection, and T_w is the time constant of the signal washout. In this research, PSS which feeds back the generator angular velocity deviation $\Delta\omega$ is assumed. When feeding back the generator output deviation ΔP, there is the necessity to carry out synchronized measurement of the ΔP, or identify the ΔP from the measured phasors.

Here, the coupled vibration model (6) is extended for including the effect of PSSs:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \\ \dot{\boldsymbol{x}}_{\mathrm{PSS1}} \\ \dot{\boldsymbol{x}}_{\mathrm{PSS2}} \end{bmatrix} = \begin{bmatrix} a'_1 & a'_2 & a'_3 & a'_4 & \boldsymbol{c}_1{}^T \\ 1 & 0 & 0 & 0 & \boldsymbol{0}^T \\ b'_1 & b'_2 & b'_3 & b'_4 & \boldsymbol{c}_2{}^T \\ 0 & 0 & 1 & 0 & \boldsymbol{0}^T \\ \boldsymbol{d}_1 & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{D}_1 \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{d}_2 & \boldsymbol{0} & \boldsymbol{D}_2 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ \boldsymbol{x}_{\mathrm{PSS1}} \\ \boldsymbol{x}_{\mathrm{PSS2}} \end{bmatrix} \quad (8)$$

where $\boldsymbol{x}_{\mathrm{PSS}k}$ ($k = 1, 2$) is the vector of state variables of PSS defined by

$$\boldsymbol{x}_{\mathrm{PSS}k} = \begin{bmatrix} v_{1k} & v_{2k} & v_{3k} & v_{4k} \end{bmatrix}^T \quad (9)$$

$$v_{1k} \equiv \Delta V_{\mathrm{PSS}k} \ \text{(PSS output)}. \quad (10)$$

Variables x_2 and x_4 are directly measured by PMUs. Other ones can be calculated by the relations of $x_1 = \dot{x}_2$, $x_3 = \dot{x}_4$, and (7) from the measured x_2 and x_4.

The vector $\boldsymbol{c}_k$ is calculated simultaneously with a'_i and b'_i ($i = 1 \sim 4$) by the least squares method. Note that only one of the elements of $\boldsymbol{c}_k$ associated with the PSS output (v_{1k}) has any value, while all other elements are equal to zero, that is,

$$\boldsymbol{c}_1{}^T = \begin{bmatrix} c_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (11)$$

$$\boldsymbol{c}_2{}^T = \begin{bmatrix} 0 & 0 & 0 & 0 & c_2 & 0 & 0 & 0 \end{bmatrix}. \quad (12)$$

The 4×1 vector $\boldsymbol{d}_k$ and the 4×8 matrix $\boldsymbol{D}_k$ are determined by the real structure of object PSS, that is, these include the parameters K_k and $T_{1k}, \cdots, T_{4k}$.

The stability of dominant modes is evaluated by eigenvalues of the matrix of (8). Two PSSs are tuned based on the model (8) since vectors $\boldsymbol{d}_k$ and matrices $\boldsymbol{D}_k$ include parameters of PSSs, that is, the change of parameters affect eigenvalues directly. Tuned parameter sets are expected to stabilize at least two modes although they could not be optimum sets. The effectiveness of tuning can be assessed more properly by evaluating the eigenvalues of (8) modeled again with the measurement data after tuned control are applied. Thus, PSS parameters can be tuned based on the small oscillation data obtained by the wide area phasor measurement.

3.2 Gradual tuning of PSSs

New parameter sets of PSSs obtained by the above approach are the final goal of tuning control. However, obtained parameter sets might be unexpected ones for an error in the calculation process, a large noise in the measurement data, a sudden change of the system state, and so on. Therefore, PSSs have to be tuned by gradual steps for the security of the power system. This gradual tuning approach is applicable in the case of other methods for tuning parameters of PSSs, for example, based on a system identification, a genetic algorithm, a fuzzy logic, and so on.

The procedure for tuning of PSSs based on the wide area phasor measurement using an extended coupled vibration model consists of the following steps.

1. Select three measurement sites, which participate significantly in the dominant and the quasi-dominant modes. One of them is for the reference of the phase angle, and other two are targets of tuning control.
2. Obtain the oscillation data of these sites. Steady state phasor fluctuations measured in the normal operation are available. Note that phasors are stored with the observed time by using PMUs synchronized by the GPS signal. Therefore, measured phasors are directly comparable with each other without considering the delay in the communication.
3. Extract inter-area oscillations by applying the discrete Wavelet transformation to the observed phasor. The time series data sets of the state variables of PSSs are provided by calculating (7) in the time domain.
4. Determine coefficients a'_i, b'_i, and c_k of the coupled vibration model (8) by the least squares method.
5. Find appropriate parameter sets of PSSs based on the model (8).
6. Tune PSSs step by step toward the parameter sets obtained above. In each step, the effect of tuning is assessed by eigenvalues of (8) modeled again using the phasor fluctuations after tuning control.
7. By repeating the gradual tuning and the stability assessment, PSSs are tuned appropriately.

In this paper, a coupled vibration model with two dominant electro-mechanical modes associated with the angle stability is discussed. Therefore, this approach is applicable in the case that a dominant and a quasi-dominant modes are classified while the measurement sites participating in these modes are specified. Note that the application of this approach is not limited to the power system with longitudinal configuration used in this study.

4 ASSESSMENT IN A TEN-MACHINE SYSTEM

4.1 System configuration

The proposed method is applied to a ten-machine longitudinally interconnected system. Figure 1 shows the configuration of IEEJ WEST 10-machine system model [9]. This system represents the power system model of the western 60 Hz areas of Japan. System constants and generation capacity of generators are shown in Tables 6 and 7 in APPENDIX, respectively. Active power of all loads is assumed to be constant current, and reactive power is constant impedance. In Figure 1, (P) denotes the generation and loading condition in the daytime, and (N) denotes the condition in the nighttime. The unit is 1,000 MVA base per unit.

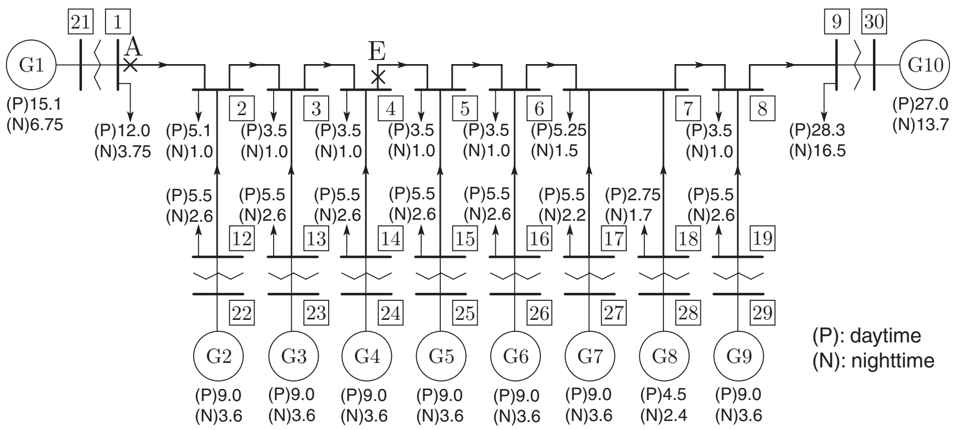

Figure 1: IEEJ WEST 10-machine system model. The unit is 1,000 MVA base per unit.

Each generator is equipped with an AVR shown in Figure 2, and generators 1 and 5 are equipped with $\Delta\omega$-type power system stabilizer to damp inter-area oscillations. In this study, the time lag for the signal detection and the time constant of the signal washout are $T_0 = 0.02$ (s), $T_w = 5.0$ (s), respectively. In the initial condition, the parameter setting of PSS is $K = 0.20$, $T_1 = 1.66$, $T_2 = 1.51$, $T_3 = 2.07$, $T_4 = 0.01$, and two generators are equipped with the identical PSS. In this study, the software for the simulation of power system dynamics, EUROSTAG [10], is used for the time domain simulation.

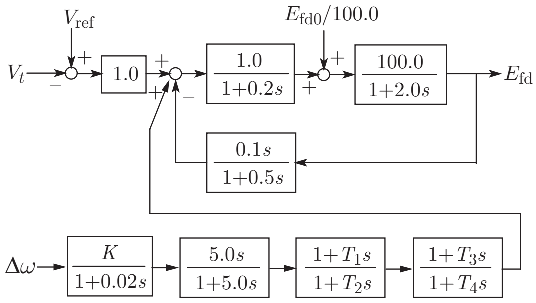

Figure 2: Exciter model with $\Delta\omega$ type Power System Stabilizer.

4.2 Oscillation characteristics

Figure 3 shows the real part of the right eigenvectors corresponding to the generator rotor angle calculated by (17) in the daytime loading condition. The matrix A, which is the linearization of the full system at the operating point, is obtained by using the power system simulation package. Mode 1 denotes the dominant mode, and mode 2 denotes the quasi-dominant mode. This result shows that mode 1 oscillates in the opposite direction between both end generators 1 and 10, while mode 2 oscillates between both end generators 1, 10 and the middle generator 5. Figure 4 shows participation factors corresponding to the generator rotor angle calculated by using (20). These results show that generators 1, 5, and 10 participate principally in modes 1 and 2. Here, the coupled vibration model is calculated by using the voltage phasor of nodes 21 and 25 with node 30 as a reference.

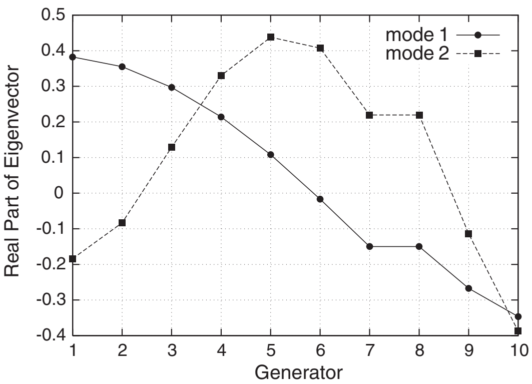

Figure 3: Mode shape of the dominant (mode 1) and the quasi-dominant (mode 2) modes.

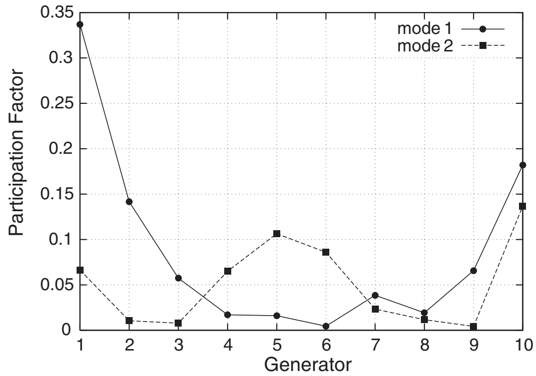

Figure 4: Participation factors associated with the generator angle.

4.3 Tuning of PSSs in the daytime loading condition

In this study, some small load variations at some load buses are assumed to simulate the phasor fluctuations measured in the real power system. The extended coupled vibration model (8) is modeled by using these small oscillations. Table 1 shows the variation of eigenvalues when each parameter of PSS equipped with the generator 1 is changed. The second column of the table shows eigenvalues of dominant low-frequency modes calculated by using the power system simulation package. The third column shows eigenvalues of corresponding two modes of the approximate model (8). The result shows that the approximate model estimates two conjugate eigenvalues properly. In addition, the trend of the variation of both eigenvalues with parameter change coincides well with each other. Therefore, the extended coupled vibration model can evaluate the stability change with tuning of PSS parameters correctly. The advantage of this approach is that dominant modes can be estimated by using steady state phasor fluctuations measured in the normal operating condition.

parameter	full system	approx. model
initial condition	$-0.065 \pm j1.731$ $-0.154 \pm j4.055$	$-0.080 \pm j2.223$ $-0.182 \pm j3.832$
$K = 0.02$	$-0.048 \pm j1.714$ $-0.152 \pm j4.050$	$-0.074 \pm j2.152$ $-0.179 \pm j3.815$
$K = 0.4$	$-0.080 \pm j1.751$ $-0.157 \pm j4.061$	$-0.085 \pm j2.292$ $-0.184 \pm j3.847$
$T_1 = 2.16$	$-0.071 \pm j1.735$ $-0.155 \pm j4.057$	$-0.082 \pm j2.248$ $-0.183 \pm j3.835$
$T_1 = 1.16$	$-0.058 \pm j1.728$ $-0.153 \pm j4.054$	$-0.078 \pm j2.196$ $-0.181 \pm j3.828$
$T_2 = 2.01$	$-0.059 \pm j1.728$ $-0.154 \pm j4.054$	$-0.078 \pm j2.201$ $-0.181 \pm j3.828$
$T_2 = 1.01$	$-0.076 \pm j1.736$ $-0.156 \pm j4.058$	$-0.083 \pm j2.261$ $-0.183 \pm j3.836$
$T_3 = 2.57$	$-0.070 \pm j1.735$ $-0.155 \pm j4.057$	$-0.082 \pm j2.243$ $-0.183 \pm j3.835$
$T_3 = 1.57$	$-0.060 \pm j1.728$ $-0.154 \pm j4.054$	$-0.078 \pm j2.202$ $-0.181 \pm j3.828$
$T_4 = 0.51$	$-0.048 \pm j1.732$ $-0.150 \pm j4.052$	$-0.075 \pm j2.154$ $-0.179 \pm j3.826$

Table 1: The comparison of eigenvalues variation of the full system model with of the approximate model when a parameter of PSS equipped with the generator 1 is changed in the daytime loading condition.

Table 2 shows the result of tuning of PSSs based on the approximate model (8). The parameter sets of PSSs are determined to improve damping ratios of two low-frequency modes of the model, that is, to maximize the following objective function J under the constraint that all eigenvalues lie on the left-hand side of the complex plane:

$$\max J = \min_i \frac{-\Re(\lambda_i)}{\sqrt{\Re(\lambda_i)^2 + \Im(\lambda_i)^2}} \tag{13}$$

subject to

$$^\forall \Re(\lambda_i) < 0 \quad (i = 1, \cdots, n) \tag{14}$$

where λ_i is the i-th eigenvalue of the model (8). The optimization is implemented by using a MATLAB Toolbox for genetic algorithm [11].

parameter	initial	G1	G5
K	0.20	0.37	0.23
T_1	1.66	1.82	2.64
T_2	1.51	0.83	0.64
T_3	2.07	2.31	2.09
T_4	0.01		

Table 2: The result of tuning of PSSs in the daytime condition.

Table 3 shows parameter settings for five steps of gradual tuning of PSS equipped with the generator 1. One wrong case with the opposite direction of parameter tuning is also considered for investigating the accuracy of the proposed method. Table 3 also shows eigenvalues of the coupled vibration model (8) and damping ratios in each parameter setting. The result shows that two dominant modes are stabilized gradually with the parameter change from the initial parameter set to the final set. On the other hand, in the wrong case, two modes are destabilized with the change of parameters. In the case of PSS equipped with the generator 5, similar results have been obtained. These results show that appropriate parameters of PSSs can be obtained and the stability change can be assessed correctly by using the coupled vibration model.

Figure 5 shows the simulation results when two tuned PSSs are applied simultaneously. Here, an assumed disturbance is a three phase ground fault at point E in the double circuit transmission line shown in Figure 1. The fault is cleared at 0.07 sec after the fault occurred. The result shows that low-frequency oscillation is damped effectively by tuned PSSs. On the other hand, the critical clearing time is 0.091 sec in the initial condition, while it is improved up to 0.142 sec with tuned PSSs.

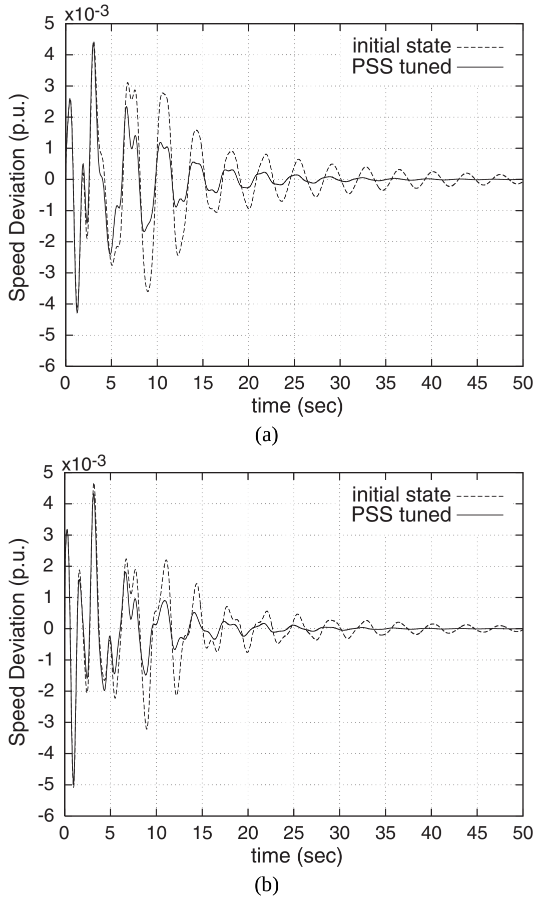

Figure 5: Simulation with PSSs of generators 1 and 5 tuned in the daytime condition. (a) Generator 1. (b) Generator 5.

parameter sets	K	T_1	T_2	T_3	T_4	eigenvalues of the approx. model	damping ratio (%)
wrong	0.16	1.63	1.66	2.02	0.01	$-0.0781 \pm j2.1976$ $-0.1808 \pm j3.8266$	3.554 4.720
initial	0.20	1.66	1.51	2.07	0.01	$-0.0801 \pm j2.2230$ $-0.1816 \pm j3.8316$	3.601 4.735
1st	0.24	1.69	1.36	2.12	0.01	$-0.0822 \pm j2.2521$ $-0.1828 \pm j3.8369$	3.646 4.759
2nd	0.28	1.72	1.21	2.17	0.01	$-0.0845 \pm j2.2868$ $-0.1841 \pm j3.8426$	3.691 4.786
3rd	0.32	1.75	1.06	2.22	0.01	$-0.0866 \pm j2.3250$ $-0.1854 \pm j3.8478$	3.723 4.812
4th	0.36	1.78	0.91	2.27	0.01	$-0.0886 \pm j2.3644$ $-0.1868 \pm j3.8522$	3.744 4.843
final	0.37	1.82	0.83	2.31	0.01	$-0.0894 \pm j2.3836$ $-0.1876 \pm j3.8531$	3.749 4.862

Table 3: The stability change with gradual tuning of PSS equipped with the generator 1.

4.4 *Tuning of PSSs in the nighttime loading condition*

The proposed method is applied to a different loading condition. The loading condition denoted by (N) in Figure 1 is used in this analysis. Table 4 shows the comparison of eigenvalues calculated by using the full system matrix with the approximate coupled vibration model. The result shows that the approximate model evaluates successfully the slight change of eigenvalues.

parameter	full system	approx. model
initial condition	$-0.1021 \pm j2.7001$ $-0.1912 \pm j5.0542$	$-0.0875 \pm j2.7733$ $-0.2346 \pm j4.3954$
$K = 0.02$	$-0.0996 \pm j2.6966$ $-0.1902 \pm j5.0497$	$-0.0872 \pm j2.7699$ $-0.2341 \pm j4.3900$
$K = 0.4$	$-0.1049 \pm j2.7040$ $-0.1924 \pm j5.0591$	$-0.0878 \pm j2.7771$ $-0.2358 \pm j4.4002$
$T_1 = 2.16$	$-0.1032 \pm j2.7011$ $-0.1918 \pm j5.0557$	$-0.0878 \pm j2.7747$ $-0.2352 \pm j4.3969$
$T_1 = 1.16$	$-0.1010 \pm j2.6992$ $-0.1907 \pm j5.0527$	$-0.0870 \pm j2.7716$ $-0.2344 \pm j4.3930$
$T_2 = 2.01$	$-0.1013 \pm j2.6993$ $-0.1908 \pm j5.0530$	$-0.0873 \pm j2.7724$ $-0.2347 \pm j4.3929$
$T_2 = 1.01$	$-0.1040 \pm j2.7014$ $-0.1923 \pm j5.0565$	$-0.0888 \pm j2.7765$ $-0.2354 \pm j4.3979$
$T_3 = 2.57$	$-0.1029 \pm j2.7010$ $-0.1916 \pm j5.0554$	$-0.0876 \pm j2.7744$ $-0.2351 \pm j4.3965$
$T_3 = 1.57$	$-0.1013 \pm j2.6993$ $-0.1908 \pm j5.0530$	$-0.0873 \pm j2.7725$ $-0.2347 \pm j4.3931$
$T_4 = 0.51$	$-0.0984 \pm j2.6990$ $-0.1885 \pm j5.0503$	$-0.0651 \pm j2.7355$ $-0.2300 \pm j4.3518$

Table 4: The comparison of eigenvalues variation of the full system model with of the approximate model when a parameter of PSS equipped with the generator 1 is changed in the nighttime loading condition.

Table 5 and Figure 6 show the results of tuning of PSSs. An assumed disturbance is the same fault at point A in Figure 1, where it is cleared at 0.07 sec after the fault occurred. And the critical clearing time is improved from 0.070 sec up to 0.087 sec. These results demonstrate the effectiveness of the proposed approach based on the wide area phasor measurement.

parameter	initial	G1	G5
K	0.20	0.31	0.67
T_1	1.66	4.52	1.91
T_2	1.51	0.68	0.43
T_3	2.07	3.58	2.98
T_4	0.01		

Table 5: The result of tuning of PSSs in the nighttime condition.

5 CONCLUSIONS

In this paper a method for tuning power system stabilizers based on the wide area phasor measurement is developed. A coupled vibration model has been developed to detect inter-area low-frequency modes from the measurement data. Especially, the coupled vibration model has been extended to include the effect of power system stabilizers.

In this study, the effectiveness of the proposed method has been investigated by using the oscillation data obtained by a power system simulation package. The method has been applied to a ten-machine longitudinally interconnected power system. The results have demonstrated that inter-area modes could be identified correctly by using steady state phasor fluctuations. On the other hand, PSSs have been tuned by gradual steps toward the parameter sets determined by using the extended coupled vibration model. The effect of the tuned control has been assessed by the coupled vibration model. Correct tuning and evaluation has been demonstrated in numerical studies.

APPENDIX

1. Investigation of oscillation characteristics

A power system is described by the following differential equation:

$$\dot{\boldsymbol{x}} = f(\boldsymbol{x}),\ \boldsymbol{x} \in \mathbf{R}^n. \quad (15)$$

The linearization of $f(\boldsymbol{x})$ at a equilibrium point $\boldsymbol{x} = \boldsymbol{x}_1$ is represented by

$$\dot{\boldsymbol{x}} = A\boldsymbol{x},\ A \equiv D_{\boldsymbol{x}} f(\boldsymbol{x}_1). \quad (16)$$

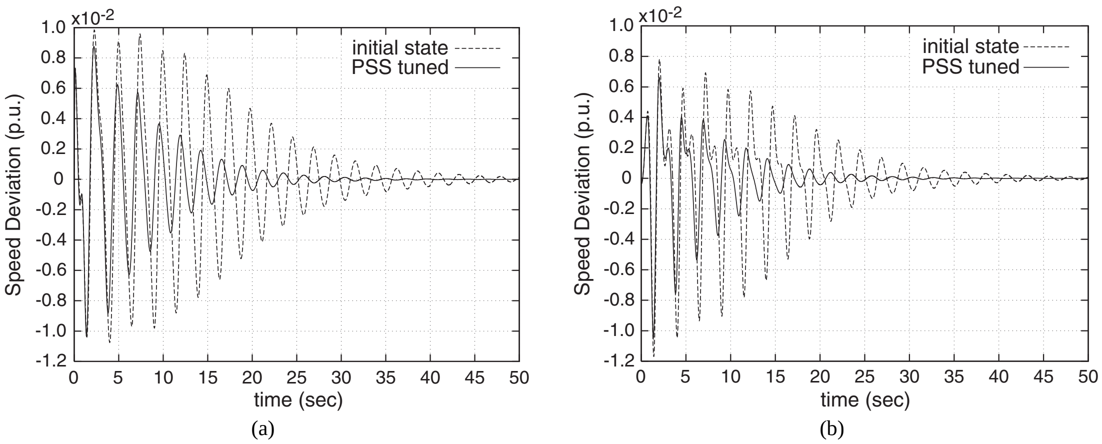

Figure 6: Simulation with PSSs of generators 1 and 5 tuned in the nighttime condition. (a) Generator 1. (b) Generator 5.

The right eigenvector $\boldsymbol{u}_i$ and the left eigenvector $\boldsymbol{v}_i$ of the matrix A are defined by

$$A\boldsymbol{u}_i = \boldsymbol{u}_i\lambda_i,\ \boldsymbol{u}_i \neq 0 \tag{17}$$

$$\boldsymbol{v}_i{}^T A = \lambda_i \boldsymbol{v}_i{}^T,\ \boldsymbol{v}_i \neq 0 \tag{18}$$

where λ_i is the i-th eigenvalue of the matrix A. Here, these eigenvectors are normalized to satisfy the following condition:

$$\boldsymbol{v}_i{}^T \boldsymbol{u}_j = \begin{cases} 1 & \text{if } i = j \\ 0 & \text{otherwise} \end{cases} \tag{19}$$

Thus, the participation factor is given by

$$p_{ki} = u_{ki} v_{ik}. \tag{20}$$

The participation factor p_{ki} represents a measure of the participation of the k-th machine state in the trajectory of the i-th mode [12]. When the condition (19) is satisfied, the summation of all elements of each row or column of the participation matrix $P = \{p_{ij}\}$ is always unity. Therefore, the participation factor is dimensionless. The oscillation characteristics of a power system are investigated by using eigenvectors and the mode-machine participation is measured by using the participation factor.

2. System constants

Generator: Park's 5th model, 1000 MVA base		
$x_d = 1.70$ (p.u.)	$x'_d = 0.35$ (p.u.)	$x''_d = 0.25$ (p.u.)
$x_q = 1.70$ (p.u.)	$x''_q = 0.25$ (p.u.)	$X_l = 0.225$ (p.u.)
$T'_d = 1.00$ (s)	$T''_d = 0.03$ (s)	$T''_q = 0.03$ (s)
$T_a = 0.40$ (s)	$M = 7.00$ (s)	
Transmission system: 1000 MVA, 500 kV base, 60 Hz		
Impedance: $Z = 0.0042 + j0.1260$ (p.u.)/100km		
Electrical charge capacity: $jY/2 = j0.0610$ (p.u.)/100km		
Transformer: $x_t = 0.14$ (p.u.)		
Interconnected line: 100 km, double circuit		
Line to generator: 50 km (G8: 100 km), double circuit		

Table 6: System constants of IEEJ WEST10-machine system.

	daytime (MVA)	nighttime (MVA)
G1	15,000	9,000
G8	5,000	3,000
G10	30,000	18,000
Others	10,000	6,000
Total sum	120,000	72,000

Table 7: Generator rated capacity.

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