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Full Length Research Paper

Selection of optimum location of power system stabilizer in a multimachine power system

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In this paper an attempt has been made to propose a new technique for selection of optimum site of a power system stabilizer (PSS) to mitigate the small-signal stability problem in a multimachine power system. Study reveals that the PSS displaces the swing mode from its critical position to a more desirable position changing the response of the excitation system. Based on the change of the exciter transfer function with respect to the PSS transfer function, an Optimum PSS Location Index (OPLI) has been introduced and used to identify the best location of the PSS in a multimachine system. The analysis of the effect of load on eigenvalues confirms that the prediction of best location of PSS by OPLI method is more effective in enhancing the small-signal stability of the system.

Key words: Critical swing mode, optimum PSS location index, sensitivity of PSS effect, small signal stability.

INTRODUCTION

The enhancement of damping of electromechanical oscillations in multimachine power systems by the application of a Power System Stabilizer (PSS) has been a subject of great attention in the past three decades (Larsen et al., 1981; Abe et al., 1983; Hsu et al., 1988; Kundur et al., 1989; Klein et al., 1992; Zhou et al., 1992; Ao et al., 1994; Rogers, 2000). It is much more significant today when many large and complex power systems frequently operate close to their stability limits. Though, there is common perception that the application of PSS is almost a mandatory requirement on all generators in modern power network but in developing countries, where power networks are mostly longitudinal in nature, constrained economy limits the use of high price PSS with each and every generator. In view of the potentially high cost of using a PSS and to assess its effectiveness in damping poorly damped swing modes to achieve better stability, identification of the optimum site of PSS is still an important task to the researcher. The issue of suitably choosing the location of a PSS in a multimachine system has been first investigated by deMello et al. (1980).

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A coherency-based identification method was proposed by Hiyama (1983), where a quadratic performance index determines the most suitable location of the PSS for the coherent group. A new coordinated synthesis method was proposed by Doi and Abe (1984), by combining eigenvalue sensitivity analysis and linear programming to select the machine to which the PSS can be effectively applied. The concept of the participation-factor was used by Chen and Hu (1988), where the machine having the greatest participation factor for the most poorly damped swing mode is chosen as the optimum site for the stabilizer location. The concept of the participation-factor is extended further by Ostojc (1988), by introducing a new coupling-factor. In order to investigate the effects of control input on the modes, in Chiang and Thorp (1990), the authors have taken the control matrix B into consideration and have used a certain type of PSS which can effectively determine the optimum location. Another efficient algorithm which involves the calculation of transfer function residues was presented by Martins and Lima (1990). The control effect of PSS on eigenvector and its application was presented in a dominant method by Zhou et al. (1991a). Here the authors introduced the concept of Sensitivity of PSS Effect (SPE) based on the product of the right and left-eigenvector entries for the corresponding input state of the PSS and the state corresponding to the control effect of PSS. Another popular technique was reported by Wang et al. (1997), which uses the damping-torque analysis (DTA) method. Here, the best location of the PSS is determined from a group of proposed indices. A new technique called eigensolution free method based on reduced-order modal control analysis was reported by Liu and Peng (2004). Recently a powerful optimization technique, Genetic Algorithm (GA), was used by Sebaa and Boudour (2006) to select the optimum location and design of a robust multimachine PSS.

In the present work, a simple and straight-forward approach is proposed using the change of response of the excitation system with respect to the response of PSS in a certain swing mode (λ'). A new index, called Optimum PSS Location Index (OPLI) has been introduced. As the PSS acts through the excitation system, it was found that the magnitude of OPLI is large for that machine where the effect of PSS on the exciter is large. The advantage of this method is that, it is possible to identify the best installing location of PSS from the knowledge of the oscillation mode (λ') of interest and the transfer function of the excitation system of the respective machine only.

In the following section, a full-order multimachine model including a first-order power system stabilizer with all network dynamics has been considered. An example of a 3-machine, 9-bus system has been adopted and the PSS is applied sequentially to each machine and the improvement in damping of the critical mode of the system has been observed. Next the optimum location of PSS is searched through the proposed new method of Optimum PSS Location Index (OPLI) and it appears that the new method gives a similar prediction of PSS location as obtained using the existing SPE method (Zhou et al., 1991a). Finally the effect of load variation on eigenvalues has been investigated and it was observed that the PSS improves small-signal stability and gives maximum improvement when installed at the optimum location. The new OPLI method seems to be more superior and acceptable than the existing SPE method, as it considers the full order multimachine linearized model including all type of network buses, where as the SPE method has used the reduced-order multimachine linearized model considering generator buses only eliminating other network buses.

THEORY

Multimachine linearized model with power system stabilizer and network dynamics

The general theory of small-signal stability problem in case of multimachine system and its linearized-model with IEEE-Type I exciter was described by Sauer and Pai (1998). When a PSS is installed in a multimachine system, where the output of the PSS acts through the excitation system (Sauer and Pai, 1998), the linearized differential algebraic model about any operating point can be expressed as:

$$\Delta\dot{X} = A_1\Delta X + B_1\Delta I_g + B_2\Delta V_g + E_1\Delta U \quad (1)$$

$$0 = C_1\Delta X + D_1\Delta I_g + D_2\Delta Vg \quad (2)$$

$$0 = C_2\Delta X + D_3\Delta I_g + D_4\Delta V_g + D_5\Delta V_l \quad (3)$$

$$0 = D_6\Delta V_g + D_7\Delta V_l \quad (4)$$

Where

$$X = \left[X_1^T \quad X_2^T \quad . \quad . \quad . \quad X_m{}^T\right]^T,$$

$$X_i = \left[\delta_i \quad \omega_i \quad E'_{qi} \quad E'_{di} \quad E_{fdi} \quad V_{Ri} \quad R_{Fi} \quad V_{si}\right]^T,$$

$$I_g = \left[I_{d1} \quad I_{q1} \quad I_{d2} \quad I_{q2} \quad . \quad . \quad . \quad I_{dm} \quad I_{qm}\right]^T,$$

$$V_g = \left[\theta_1 \quad V_1 \quad \theta_2 \quad V_2 \quad . \quad . \quad . \quad \theta_m \quad V_m\right]^T,$$

$$V_l = \left[\theta_{m+1} \quad V_{m+1} \quad \theta_{m+2} \quad V_{m+2} \quad . \quad . \quad . \quad \theta_n \quad V_n\right]^T,$$

$$U = \left[U_1^T \quad U_2^T \quad . \quad . \quad . \quad U_m{}^T\right]^T, U_i = \left[T_{Mi} \quad V_{refi}\right]^T$$

For i = 1, 2, ….., m (number of machines) and i = m+1, m+2, ……., n (number of load buses). Here (1) and (2) represent the linearized differential equations and linearized stator algebraic equations of the machine. Equation (3) and (4) correspond to the linearized network equations pertaining to the generator buses and the load buses. Eliminating ΔI_g from the respective equations the over-all state-space model is obtained as:

$$\begin{bmatrix} \Delta\dot{X} \\ 0 \end{bmatrix} = \begin{bmatrix} A' & B' \\ C' & D' \end{bmatrix} \begin{bmatrix} \Delta X \\ \Delta V_N \end{bmatrix} + \begin{bmatrix} E_1 \\ 0 \end{bmatrix} \Delta U \quad (5)$$

Where:

$\Delta V_N = \left[\Delta V_g \quad \Delta V_l\right]^T$. The system matrix A_{sys} obtained from (5) is

$$\left[A_{sys}\right]_{(7m+1)\times(7m+1)} = [A'] - [B'][D']^{-1}[C'] \quad (6)$$

The system matrix without PSS can be obtained excluding the state-space variable ΔV_{si} from (1). This model has been used for simulation and application purposes.

Criterion for identification of swing modes

The swing mode of a power system can be identified by the criterion proposed by Zhou et al. (1991b). The authors have used a swing mode identification index termed as swing-loop participation ratio. The swing modes are closely related to the electromechanical swing-loops associated with the relevant state variables like rotor angle ($\Delta\delta$) and machine speed ($\Delta\omega$). The swing-loop participation ratio (ρ_h) has been defined as:

$$\rho_h = \frac{\left|\sum_{\nu=1}^{r} P_{\nu h}\right|}{\left|\sum_{\nu=r+1}^{z} P_{\nu h}\right|} \quad (7)$$

Where $P_{\nu h}$ is the participation factor of the ν -th state variable for the *h*-th mode. '*z*' represents the total number of state variables and '*r*' represents the number of relevant states belongings to the state variable set [$\Delta\delta$, $\Delta\omega$]. The proposed criterion states that generally the oscillation frequencies of the swing modes are in the range of 0.2 - 2.5 Hz. and their swing-loop participation ratio (ρ_h) > 1.

Control effect of PSS

The PSS acts through the exciter and provides control effect to the power system under consideration. If the exciter is kept off, the PSS will have no effect on the system. The control effect of PSS on the system (by the PSS output state ΔV_{si} , and the system mode λ_j) can be measured by the following coefficient (Zhou et al., 1991a):

$$S_{ji} = \psi_{j,\Delta E_{fdi}} \quad (8)$$

For *i* = 1, 2, ….., m (number of machines). Here $\psi_{j,\Delta E_{fdi}}$ is the left eigenvector entry of *j*-th mode (λ_j) corresponding to the state variable ΔE_{fdi} .

Concept of best PSS location selection indicator

During application of PSS to a multimachine power system to achieve the largest improvement in damping, the primary task is to identify the best location of PSS. In order to take into consideration the effect of both the PSS input and the PSS control in selecting the PSS location, Sensitivity of PSS Effect (SPE) for the i-th machine was considered (Zhou et al., 1991a)

$$SPE_i = \varphi_{j,\Delta\omega_i} \psi_{j,\Delta E_{fdi}} \quad (9)$$

For *i* = 1, 2,…….., *m* (number of machines), where $\varphi_{j,\Delta\omega_i}$ is the right-eigenvector entry and $\psi_{j,\Delta E_{fdi}}$ is the left-eigenvector entry of *j*-th mode corresponding to the state $\Delta\omega_i$ and ΔE_{fdi} of the *i*-th machine. *SPE* measures both the activity of PSS input $(\Delta\omega_i)$ participating in a certain oscillatory mode as well as the control effect of PSS, on this mode. The larger the magnitude of the SPE the better the overall performance of the PSS. In a multi machine power system there may be several swing modes which are of interest and for each mode a set of {SPE_i , i =1, 2,……, m} can be calculated by (9). The SPE with largest magnitude of any *i*-th machine identifies the best location of PSS.

The newly proposed concept of Optimum PSS Location Index (OPLI) is based on the change of exciter transfer function with respect to the PSS transfer function in a certain swing mode. The PSS on a machine is a closed-loop controller which considers usually the machine speed or power as its input and introduces a damping so that the system moves from a less stable region to a more stable region. As the PSS acts through the excitation system, the effect of displacement of swing modes due to installation of PSS will change the response of the excitation system. The response of the excitation system at a swing mode λ' can be obtained by replacing λ' for's' in its transfer function $Gex(s)$. The change of response of the excitation system with respect to the PSS response for a swing mode λ' is determined by the proposed index *OPLI* which is defined by:

$$|OPLI_i| = \frac{\left|(Gex_i(\lambda') - Gex_i(\lambda^0))\right|}{|Gpss(\lambda')|} \quad (10)$$

For *i* =1, 2, ………, *m* (no. of machines).

Here λ^0 and λ' are the critical swing modes before and after the installation of PSS respectively. The magnitude of OPLI measures the effect of PSS on the exciter response in a swing mode λ' of interest. The larger the value of the OPLI the larger is the control effect of PSS on the exciter and the better is the overall performance of PSS in the power system.

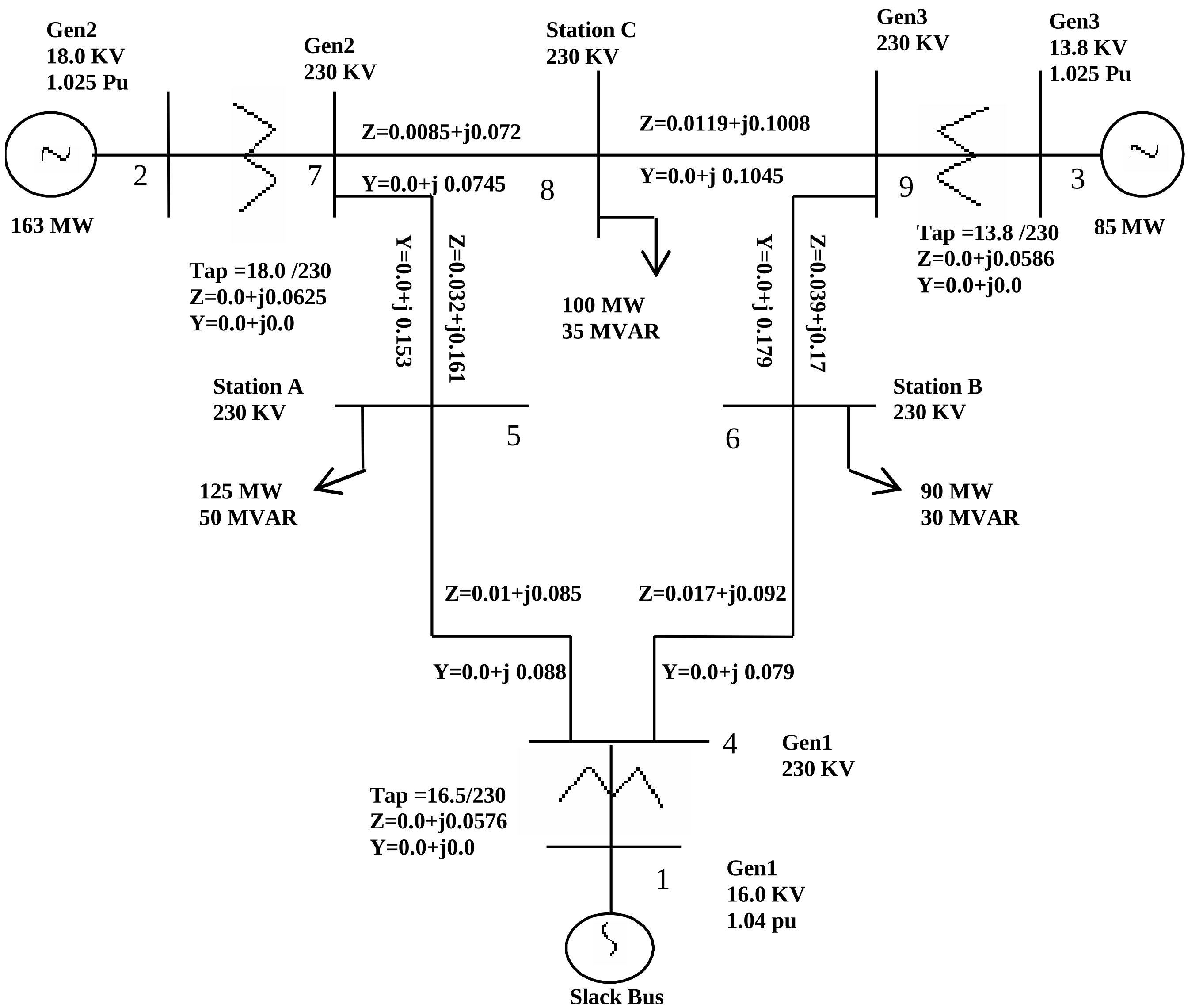

Figure 1. WSCC 3-machine, 9-bus system; the value of Y is half the line charging.

SIMULATION AND APPLICATION

Computation of eigenvalues and swing modes prior to application of PSS

The modal analysis approach using eigenvalues and swing mode computation techniques are commonly used tools (Okubo et al., 1978; Obata et al., 1981; Perez-Arriaga et al., 1982) for small signal stability problem. The popular Western System Co-coordinating Council (WSCC) 3-Machine, 9-bus system has been considered in this paper as a test case and is shown in Figure 1. Uniform damping has been assumed for all the three machines. The computed eigenvalues or the electromechanical modes of the system without PSS are listed in Table 1. It is clear from the 4th column of Table 1 that the damping ratio (ζ) of the electromechanical mode #1 (λ_1) is the smallest and therefore, the behavior of this mode is important to study the small-signal stability of the system. This mode has been referred to as the critical mode. The mode frequency and the participation factor analysis suggest that the nature of the critical mode without PSS is a local mode and is strongly associated with the machine #2 and the system states ($\Delta\delta$, $\Delta\omega$). The swing-loop participation ratio for each electromechanical mode has been shown in column 5 of Table 1, which interprets that the mode #1 and #2 are the swing modes and among which mode #1 is the most critical swing mode. Hence the power system stabilizer should

Table 1. Eigenvalues, damping ratios and swing modes of the study system prior to installation of PSS.

#	Eigen value (λ)	Frequency (*f*) Hz	Damping ratio (ζ)	Swing-loop participation ratio (| ρ_h |)
1	-2.4892 ± j10.8650	1.7290	0.2233	10.1575
2	-5.1617 ± j11.2755	1.7943	0.4162	12.4678
3	-5.3063 ± j10.3299	1.6438	0.4569	0.0406
4	-5.6837 ± j10.3601	1.6486	0.4810	0.2146
5	-5.5957 ± j10.3330	1.6443	0.4762	0.0102
6	-2.5226	0	1.0000	2.1054
7	0.0000	0	1.0000	∞
8	-0.4087 ± j 0.8293	0.1320	0.4421	0.0625
9	-0.4759 ± j 0.5616	0.0894	0.6465	0.0933
10	-0.4164 ± j 0.6618	0.1053	0.5325	0.0536
11	-3.2258	0	1.0000	0
12	-1.8692	0	1.0000	0
13	-1.6667	0	1.0000	0

Table 2. Critical swing mode and damping ratio before and after installation of PSS.

	Before installation of PSS	PSS installed at machine #1	PSS installed at machine #2	PSS installed at machine #3
Critical swing mode (λ_1)	-2.4892 + j10.8650	-2.5291 + j10.8920	-3.5586 + j10.8354	-2.4834 + j10.8865
Damping Ratio (ζ)	0.2233	0.2262	0.3120	0.2224

be placed at an optimum location, so that it can yield maximum damping to the electromechanical oscillation of the critical swing mode (#1).

Application of power system stabilizer

In this section the PSS has been applied to the proposed system (Figure 1). Though the damping of the generators of the test system is reasonably good, still small signal stability problems have been observed in the test system and hence attempts have been made to install the PSS in an optimum location in order to exhibit the improvement of critical swing mode (#1) using the PSS. The swing modes get affected with the installation of the PSS at any of the three machines. However, the response of the critical swing mode being of prime concern, it has been observed that the improvement in the critical swing mode is of highest degree (Table 2) if the PSS is installed at machine #2.

The root-locus (Figure 2b) of the critical swing mode after installation of PSS at machine #2 implies that the damping of the critical mode increases and simultaneously oscillation decreases, unlike the case for machine #1 where with PSS damping improves, but oscillation also increases (Figure 2a). With the application of PSS at machine #3, the critical mode moves towards instability with marginal increase in the gain of PSS (Figure 2c). Both the existing *SPE* and the newly proposed *OPLI* are calculated for individual machines using (9) and (10).The corresponding magnitudes of *SPE* and *OPLI* are listed in Tables 3 and 4 respectively. Considering the nature of the critical swing mode and the magnitudes of the two indicators *SPE* and *OPLI*, it is possible to conclude that the machine #2 should be the best location of PSS.

Characteristics of SPE and OPLI with PSS gain

The characteristics of OPLI with variation of PSS gain has been investigated in this section and compared with the characteristics of SPE (Figures 3a and 4a). With PSS installed at machine #1 and #2, both the SPE and OPLI characteristics show increment with increase in PSS gain. For machine #3 both of these sensitivity parameters exhibit decrement with increasing PSS gain (Figures 3c and 4c). It has been further observed that the slope of the profile of SPE as well as OPLI, both are high for optimum location of the PSS (Figures 3b and 4b). Thus it appears that the proposed index OPLI bears similar characterristics as SPE and can be effectively used instead of

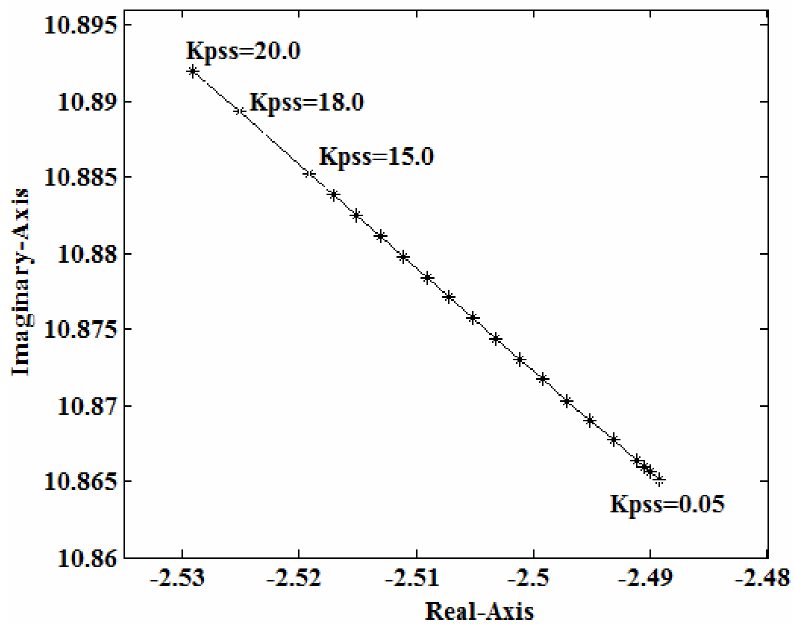

Figure 2a. Root-locus of critical swing mode when PSS installed at machine #1.

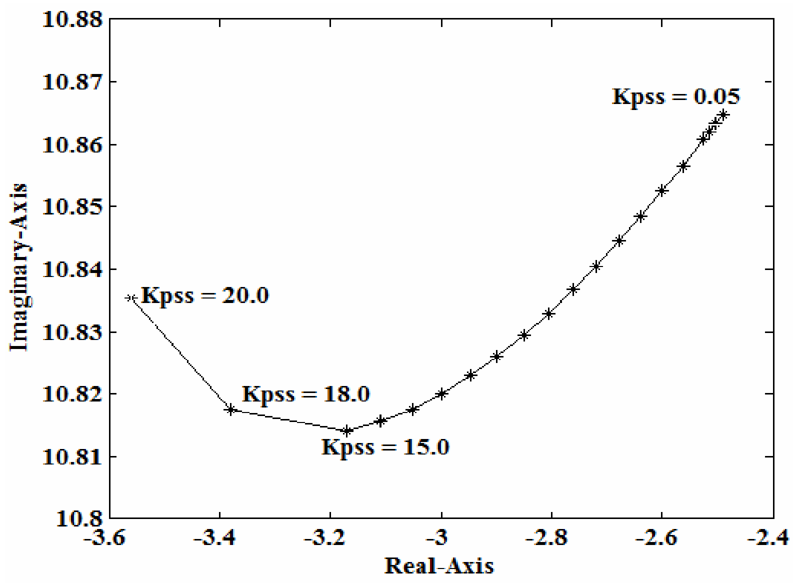

Figure 2b. Root-locus of critical swing mode when PSS installed at Machine #2.

SPE to predict the optimum location of PSS.

Effect of load increase

The real or reactive load (constant power type) at a particular bus is increased in steps.

Case 1: The real load P_L is increased at load bus #5 (heaviest load bus) from a base load 1.25 to 3.5 pu, at constant reactive load, Q_L = 0.5 pu.

Case 2: The reactive load Q_L , is increased at load bus #5 (heaviest load bus) from a base load 0.5 to 1.5 pu, at constant real load, P_L = 1.25 pu.

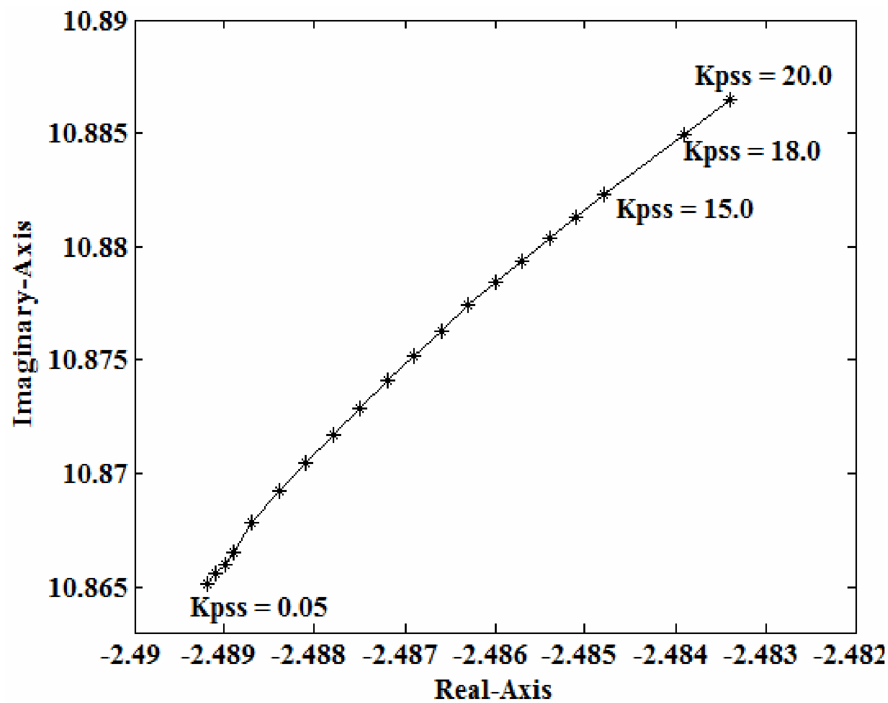

Figure 2c. Root-locus of critical swing mode when PSS installed at Machine #3.

Table 3. Magnitude of *SPE* when PSS installed at individual machine.

PSS installed at	Right-eigenvector of critical swing mode $\left|(\varphi_{1,\Delta\omega_i})\right|$	Left-eigenvector of critical swing mode $\left|(\psi_{1,\Delta E_{fdi}})\right|$	$\left|(SPE)\right|$
Machine #1 (*i* =1)	0.15345	0.0792	0.01216
Machine #2 (*i* = 2)	0.26739	1.8630	0.49814
Machine #3 (*i* = 3)	0.15627	0.0270	0.00421

Table 4. Magnitude of *OPLI* when PSS installed at individual machine.

Swing mode (λ^0) before installation of PSS	PSS installed at	Swing mode (λ') after installation of PSS	$\left|OPLI\right| = \frac{\left|(Gex(\lambda') - Gex(\lambda^0))\right|}{\left|Gpss(\lambda')\right|}$
-2.4892 + j10.8650	Machine # 1	-2.5291 + j10.8920	0.00215
	Machine # 2	-3.5586 + j10.8354	0.05174
	Machine # 3	-2.4834 + j10.8865	0.00096

When the PSS is installed at the optimum location that is machine #2, the obtained eigenvalues are represented in Table 5. This illustrates that with an increase of load (real or reactive) the system stability decreases before installation of PSS and improves significantly when PSS is installed. It has also been confirmed in this study that the relative improvement of stability at the selected optimum location of PSS is more in comparison to the other two locations (machine #1 and #3). The effect of load on SPE and OPLI have also been investigated and it was observed that even with increasing load, both the sensitivity parameters are reasonably accurate as shown

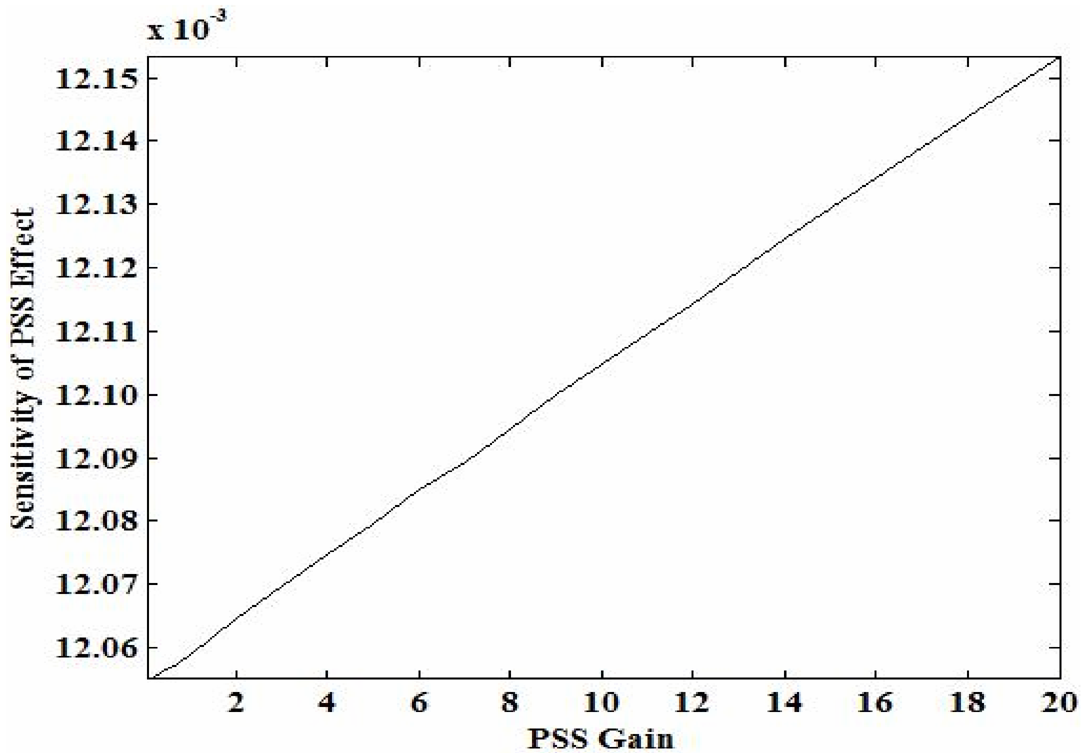

Figure 3a. *SPE* vs. PSS gain when PSS installed at Machine #1.

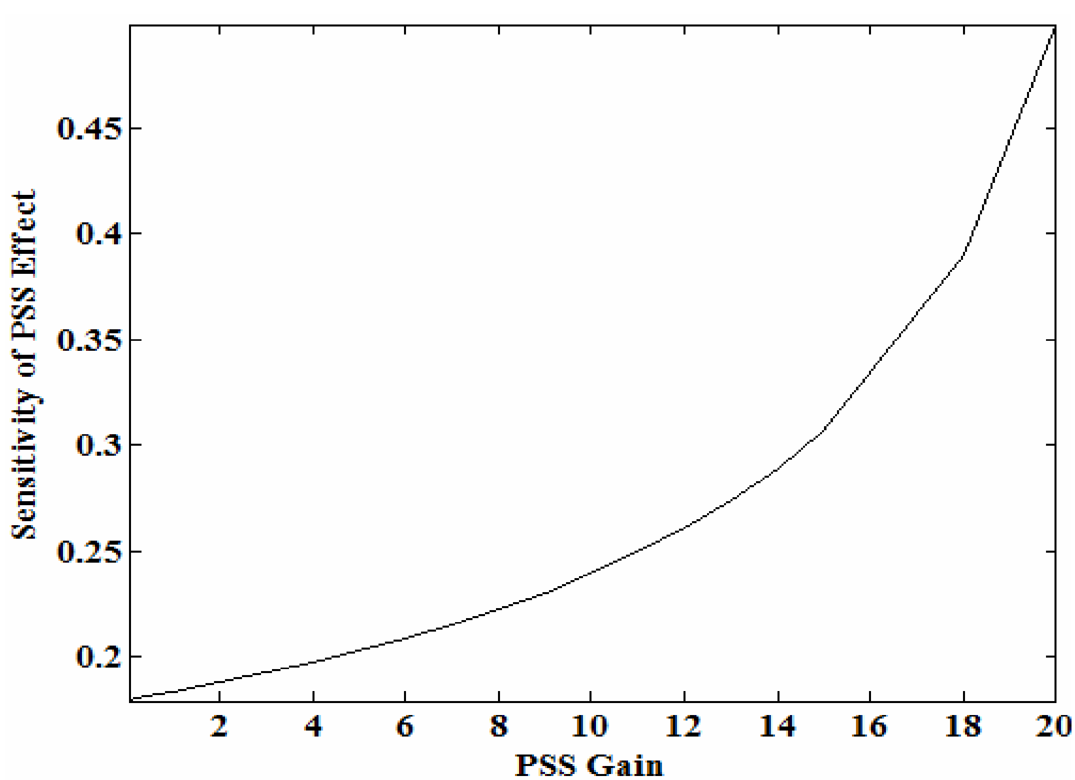

Figure 3b. *SPE* vs. PSS gain when PSS installed at machine #2.

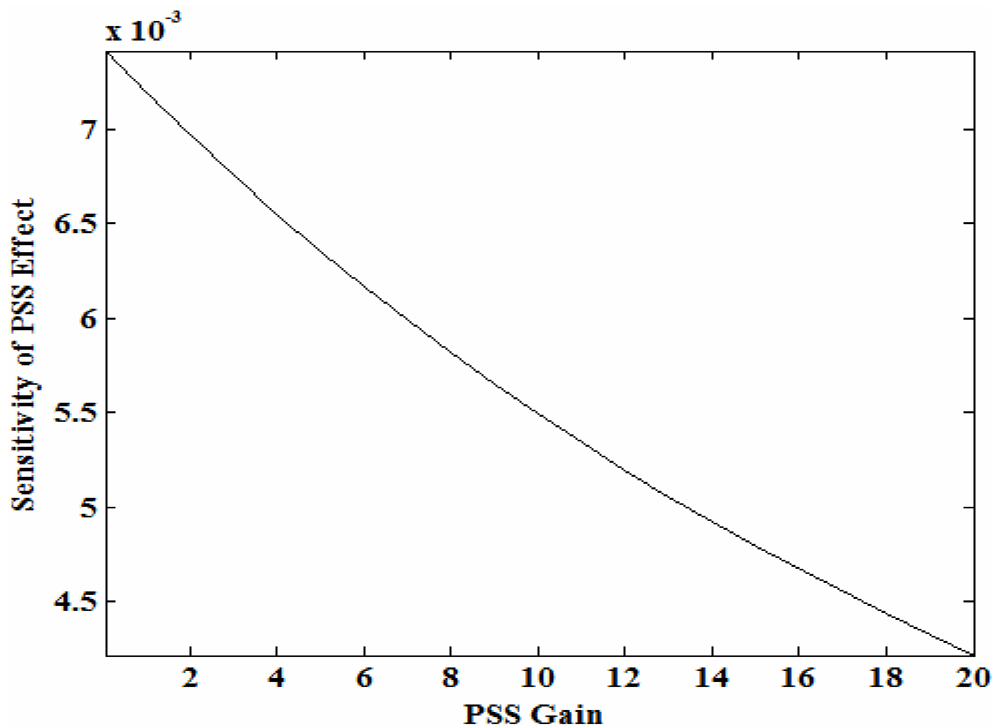

Figure 3c. *SPE* vs. PSS gain when PSS installed at machine #3.

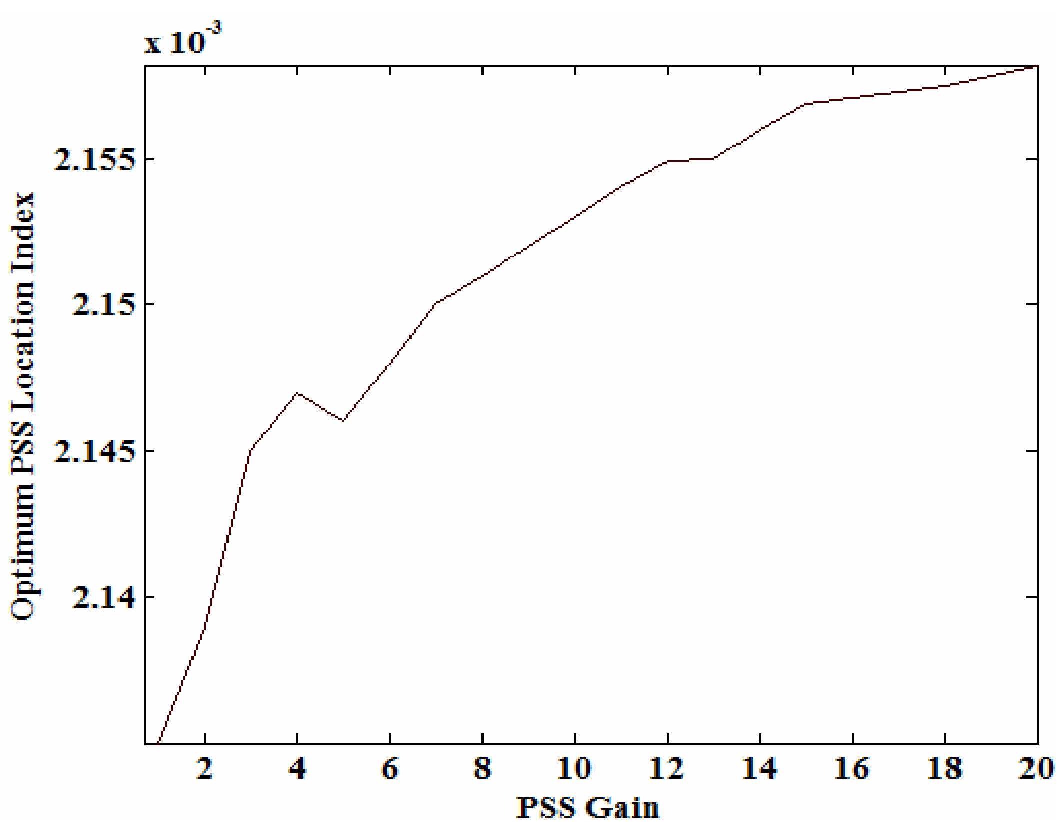

Figure 4a. *OPLI* vs. PSS gain when PSS installed at machine #1.

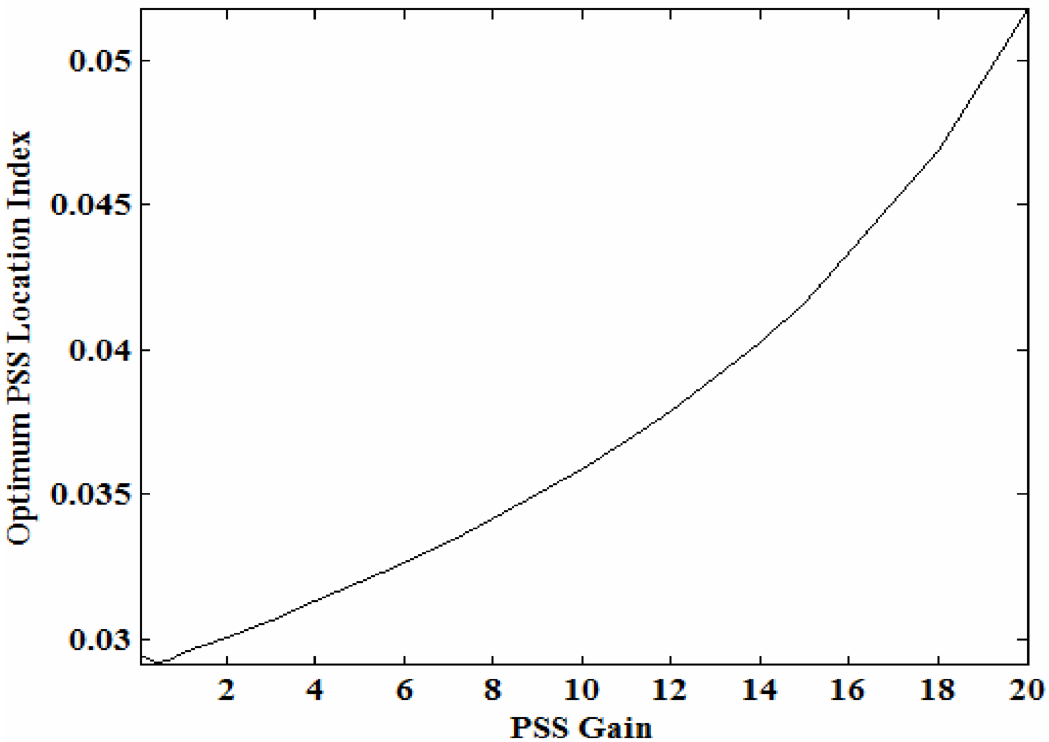

Figure 4b. *OPLI* vs. PSS gain when PSS installed at machine #2.

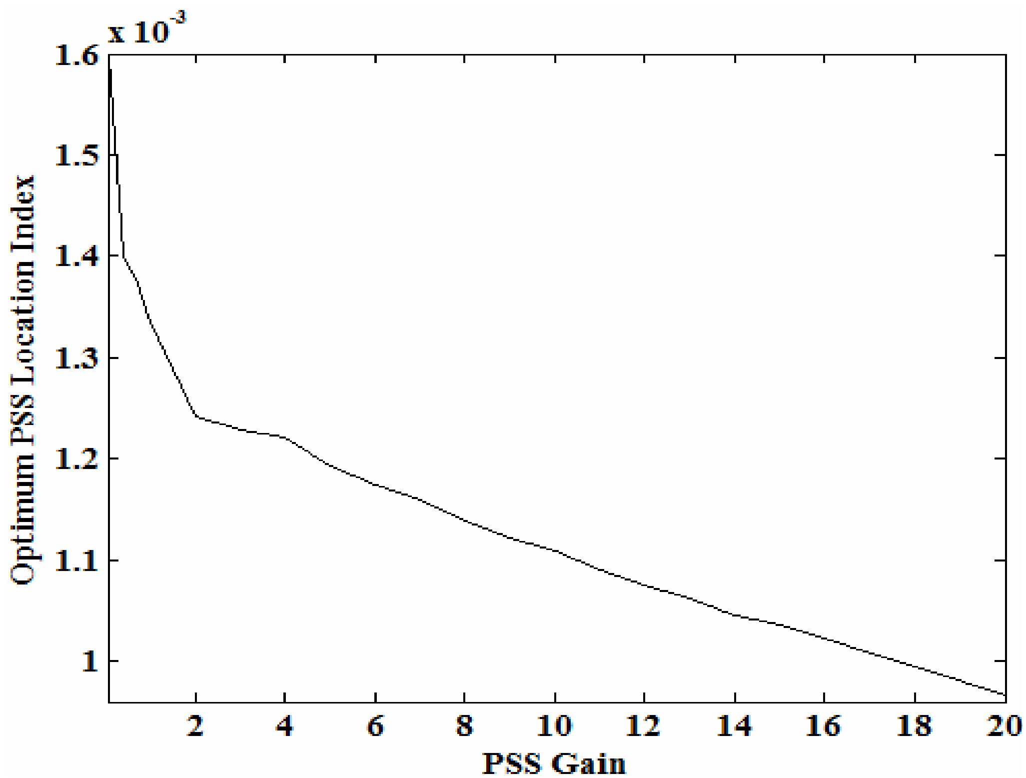

Figure 4c. O*PLI* vs. PSS gain when PSS installed at machine #3.

Table 5. Effect of load on critical swing mode.

#	Real load (P_L) (pu)	Reactive load (Q_L) (pu)	Critical swing mode (λ^0) before installation of PSS	Critical swing mode (λ') for optimum location of PSS (machine #2)
1	1.25 (Base load)	0.5	-2.4892 + j10.8650	-3.5586 + j10.8354
2	1.5	0.5	-2.4745 + j10.9692	-3.3502 + j10.9232
3	2.5	0.5	-2.4031 + j11.3400	-3.0547 + j11.3793
4	3.5	0.5	-2.3074 + j11.6323	-2.7576 + j11.6532
5	1.25	1.0	-2.4468 + j10.6290	-3.4368 + j10.4549
6	1.25	1.5	-2.4210 + j10.8862	-3.2897 + j10.8578

Table 6. Effect of Load on PSS Location Indicators.

#	Real load (P_L) (pu)	Reactive load (Q_L)(pu)	*SPE* at optimum location of PSS	*OPLI* at optimum location of PSS
1	1.25 (Base load)	0.5	0.4981	0.05174
2	1.5	0.5	0.3258	0.0395
3	2.5	0.5	0.2076	0.0239
4	3.5	0.5	0.1334	0.0145
5	1.25	1.0	0.4176	0.0537
6	1.25	1.5	0.3198	0.0395

in Table 6.

Conclusion

This paper presents a new approach to identify the optimum site for installation of power system stabilizer in a multimachine system. The procedure was based on the change of the exciter transfer function with respect to the PSS transfer function for a critical swing mode of interest. The proposed *OPLI* method and existing *SPE* method were tested for a 3- machine, 9-bus system and the obtained results revealed that both methods provide identical prediction in selecting optimum location of PSS. The present study also reveals that the proposed index is suitable for application of PSS even during heavy loading condition and till the system approaches its critical operating limit. The proposed approach appears to be more acceptable and accurate than the existing method as it considers the multimachine full-order linearized model including all network bus dynamics.

APPENDIX A

A.1 Algorithms of Calculation of OPLI

1. Derive the transfer function of the excitation system $Gex(s)$.
2. Calculate the $Gex(\lambda^0)$, here λ^0 (= -2.4892 + j 10.8650) is the critical swing mode #1, before application of PSS.
3. Install the PSS at any machine with parameters, assumed $Kpss$ =20, T_1 = 0.15 and T_2 = 0.11.

Here, $Gpss(s) = \dfrac{Kpss(sT_1 + 1)}{(sT_2 + 1)}$).

4. Compute the system matrix A_{sys} and eigenvalues after application of PSS.
5. Note the critical swing mode λ' to obtain $Gex(\lambda')$ and $Gpss(\lambda')$.
6. Calculate the *OPLI* applying (10).
7. Repeat steps 1-6 for each machine.

A.2 Transfer function of the IEEE-Type 1 exciter and results of OPLI

The state space form of the exciter is represented as:

$$\begin{bmatrix} \Delta\dot{E}_{fdi} \\ \Delta\dot{V}_{Ri} \\ \Delta\dot{R}_{Fi} \end{bmatrix} = \begin{bmatrix} f_{si}(E_{fdi}) & \dfrac{1}{T_{Ei}} & 0 \\ -\dfrac{K_{Ai}K_{Fi}}{T_{Ai}T_{Fi}} & -\dfrac{1}{T_{Ai}} & \dfrac{K_{Ai}}{T_{Ai}} \\ \dfrac{K_{Fi}}{T_{Fi}^2} & 0 & -\dfrac{1}{T_{Fi}} \end{bmatrix} \begin{bmatrix} \Delta E_{fdi} \\ \Delta V_{Ri} \\ \Delta R_{Fi} \end{bmatrix} + \begin{bmatrix} 0 \\ -\dfrac{K_{Ai}}{T_{Ai}} \\ 0 \end{bmatrix} \Delta V_{si} \quad \text{(A.1)}$$

$$\Delta E_{fdi} = [1 \quad 0 \quad 0]\begin{bmatrix} \Delta E_{fdi} \\ \Delta V_{Ri} \\ \Delta R_{Fi} \end{bmatrix} \qquad \text{(A.2)}$$

Where, $S_E(E_{fdi}) = 0.0039\exp(1.555E_{fdi})$,

$f_{si}(E_{fdi}) = \Delta S_E(E_{fdi})$ for *i* = 1, 2, 3, ……., *m* (number of machines).

Equations (A.1) and (A.2) together give the transfer function of the exciter for the *i*-th machine, $Gex_i(s) = \frac{\Delta E_{fdi}(s)}{\Delta V_{si}(s)}$. The exciter transfer function for machines #1, #2 and #3 are;

$$Gex_1 = \frac{318.4713s + 909.9181}{s^3 + 11.2452s^2 + 98.2312s + 48.4012},$$

$$Gex_2 = \frac{318.4713s + 909.9181}{s^3 + 11.9388s^2 + 103.6805s + 58.309} \quad \text{and}$$

$$Gex_3 = \frac{318.4713s + 909.9181}{s^3 + 11.4333s^2 + 99.709s + 51.088}$$

Application of PSS at machine #1

The critical swing mode, λ' = -2.5291 + j 10.8920.

$$Gpss(\lambda') = \frac{20(0.15\lambda' + 1)}{(0.11\lambda' + 1)}$$

$$Gex_1(\lambda^o) = \frac{(318.4713\lambda^o + 909.9181)}{\lambda^{o^3} + 11.2452\lambda^{o^2} + 98.2312\lambda^o + 48.4012} \quad \text{and}$$

$$Gex_1(\lambda') = \frac{(318.4713\lambda' + 909.9181)}{\lambda'^3 + 11.2452\lambda'^2 + 98.2312\lambda' + 48.4012}.$$

The $|OPLI_1| = \frac{|(Gex_1(\lambda') - Gex_1(\lambda^0))|}{|Gpss(\lambda')|} = 0.00215$.

Application of PSS at machine #2

The critical swing mode, λ' = -3.5586 + j 10.8354. The

$$|OPLI_2| = \frac{|(Gex_2(\lambda') - Gex_2(\lambda^0))|}{|Gpss(\lambda')|} = 0.05174.$$

Application of PSS at machine #3

The critical swing mode, λ' = -2.4834 + j10.8865. The

$$|OPLI_3| = \frac{|(Gex_3(\lambda') - Gex_3(\lambda^0))|}{|Gpss(\lambda')|} = 0.00096.$$

APPENDIX B

Data for the test system

B.1 Machine parameters

$R_{s1} = R_{s2} = R_{s3}$ =0.089; H_1 = 23.64, H_2 = 6.4, H_3 =3.01; $D_1 = D_2 = D_3$ = 0.2; X_{d1} = 0.269, X_{d2} = 0.8958; X_{d3} = 1.998; X'_{d1} = 0.0608, X'_{d2} = 0.1198, X'_{d3} =0.1813; X_{q1} = X'_{q1} =0.0969, X_{q2} = X'_{q2} = 0.8645, X_{q3} = X'_{q3} = 1.2578; T'_{do1} = 8.96, T'_{do2} = 6.0, T'_{do3} =5.89; T'_{qo1} = 0.31, T'_{qo2} = 0.535, T'_{qo3} =0.6.

B.2 Exciter (IEEE Type-1) parameters

$K_{A1} = K_{A2}$ = K_{A3} = 35; $T_{A1} = T_{A2} = T_{A3}$ = 0.2; $K_{E1} = K_{E2} = K_{E3}$ = 1.0; T_{E1} = T_{E2} = T_{E3} = 0.314; $K_{F1} = K_{F2} = K_{F3}$ = 0.063; $T_{F1} = T_{F2} = T_{F3}$ =0.35.

REFERENCES

Abe S, Doi A (1983). A new power system stabilizer synthesis in multimachine power systems, IEEE Trans. Power Apparatus and Systems 102(12): 3910-3918.

Chen CL, Hu YY (1988). An efficient algorithm for design of decentralized output feedback power system stabilizer, IEEE Trans. on Power Systems 3(3): 999-1004.

Chiang JL, Thorp JS (1990). Identification of optimum site for power system stabilizer applications. IEEE Trans. on Power Systems 5(4):1302-1308.

deMello FP, Nolan PJ , Laskowski TF, Undrill JM (1980). Coordinated application of stabilizer in multimachine power system. IEEE Trans. on Power Apparatus and Systems 99(3): 892-901.

Doi A, Abe S (1984). Coordinated synthesis of power system stabilizers in multimachine power systems. IEEE Trans. on Power Apparatus and Systems 103(6): 1473-1479.

Hsu Y, Liu C, Lin CJ, Hung CT (1988). Application of power system stabilizers and static var compensators on a longitudinal power system. IEEE Trans. on Power Systems 3(4): 1464-1470.

Hiyama T (1983). Coherency-based identification of optimum site for

stabilizer applications, Proc. of IEE 130C(2): 71-74.
Kundur P, Klein M, Rogers GJ, Zywno MS (1989). Application of power system stabilizers for enhancement of overall system stability. IEEE Trans. on Power Systems 4(2): 614-626.
Klein M, Rogers GJ, Moorty S, Kundur P (1992). Analytical investigation of factors influencing power system stabilizers performance. IEEE Trans. on Energy Convers 7(3): 382-390.
Larsen EV, Swann DA (1981). Applying power system stabilizer, part 1: General concept, part II: Performance objective and Tuning concept, part III: Practical considerations. IEEE Trans. Power Apparatus and Systems 100(12): 3017-3046.
Li H, Liu Q, Peng S (2004). Selection of suitable installing locations of PSS in large scale power systems. Proc. IEEE PowerCon on Power System Technology. Singapore pp. 1106-1110.
Martins N, Lima LTG (1990). Determination of suitable locations for power system stabilizers and static VAR compensators for damping electromechanical oscillations in large scale power system. IEEE Trans. on Power Systems 5(4): 1455-1469.
Ostojc DR (1988). Identification of optimum site for power system stabilizer applications, Proc. of IEE 135C(5): 416- 419.
Okubo S, Suzuki H, Uemura K (1978). Modal analysis for power system dynamic stability. IEEE Trans. on Power Apparatus and Systems 97(4): 1313-1318.
Obata Y, Takeda S, Suzuki H (1981). An efficient eigenvalue estimation technique for multimachine power system dynamic stability analysis. IEEE Trans. on Power Apparatus and Systems 100(1): 259-263.
Perez-Arriaga IJ, Verghese GC, Schweppe FC (1982). Selective modal analysis with applications to electric power system, part-II, The dynamic stability problem. IEEE Trans. on Power Apparatus and Systems 101(9): 3126-3134.
Rogers GJ (2000).The Application of Power System Stabilizers to a Multigenerator Plant. IEEE Trans. on Power Systems 15(1): 350-355.
Sebaa K, Boudour M (2006). Optimal location and tuning of robust power system stabilizers using genetic algorithm. IEEE IECon on Industrial Electronics pp. 501-506.
Sauer PW, Pai MA (1998). Power system dynamics and stability. Pearson Education Pvt. Ltd., Singapore.
Wang HF, Swift FJ, Li M (1997). Indices for selecting the best location of PSS or FACT-based stabilizers in multimachine power system: A comparative study, Proc. Inst. Elect. Engg. Gen. Trans. Distrib. 144(2): 155-159.
Z AO, Sidhu TS, Fleming RJ (1994). Stability investigation of a longitudinal power system and its stabilization by a coordinated application of power system stabilizers, IEEE Trans. on Energy Convers. 9(3): 466-474.
Zhou EZ, Malik OP, Hope GS (1992).Design of stabilizer for a multimachine power system based on the sensitivity of PSS effect. IEEE Trans. On Energy Convers. 7(3): 606-613.
Zhou EZ, Malik OP, Hope GS (1991a). Theory and method for selection of power system stabilizer location. IEEE Trans. on Energy Convers. 6(1): 170-176.
Zhou EZ, Malik OP, Hope GS (1991b). A reduced-order iterative method for swing mode computation. IEEE Trans. on Power Systems 6(3): 224-1230.