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Simultaneous Tuning of Power System Stabilizers for Enhancing the Damping Performance in Multi-Machine Power Systems

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Abstract: This study presents a simultaneous tuning of Power System Stabilizers (PSS) for enhancing the damping of low frequency electro-mechanical oscillations in a multi-machine power system using parameter-constrained non-linear optimization algorithm. The main objective of this procedure is to shift the undamped poles to the left hand side of the s-plane. In the proposed study, the parameters of each PSS controller are determined simultaneously using non-linear optimization technique. The objective of the simultaneous parameter tuning is to globally optimize the overall system damping performance by maximize the damping of all both local and inter area modes of oscillations. The results obtained from simultaneous coordinating tuning method validate the improvement in damping of the overall power system oscillations in an optimal manner. The time domain simulation results of multi-machine power system validate the effectiveness of the proposed approach. In this study, 10-machine 39-bus New England system is used as the test system.

Key words: Simultaneous tuning, PSS, non-linear optimization, quadratic programming, parameter, oscillations

INTRODUCTION

Modern power system is characterized by the extensive system interconnection and increasing dependences on the control for optimum utilizations of existing resources. Low frequency electro-mechanical oscillations are quite common problem in most interconnected power system today. These oscillations are due to the dynamic interactions between various generators of the system through its transmission network. Low frequency electro-mechanical oscillations (0.2-2.5 Hz) restrict the steady state power transfer limits which therefore affect the operational system economics and security (Hong *et al*., 1999). For the improvement of the dynamic stability of a system, Power System Stabilizers (PSS) are well known as a supplementary excitation control for intensifying the dynamic stability of the system. The addition of new damping sources (Hingorani, 1988; Larsen *et al*., 1995) together with more stressed operation in present interconnected power grids trigger the importance for methods that can handle an overall coordination for the system controllers. Conventional design approaches, like the decoupled and sequential loop closure utilized in (Taranto *et al*., 1994) cannot properly handle a truly coordinated design. Un coordinated PSSs cause destabilizing interactions. That means, PSSs add new electro-mechanical modes in to the system. So, action of damping of one electro-mechanical mode will simultaneously weaken the damping of another one. So, coordinated tuning is very essential. It will reduce the interactions with other controllers. There are so many approaches for finding solution to the problem of coordinated tuning stabilizers in multi-machine power system. Lei *et al*. (2001) presented a global tuning procedure for FACTS device Stabilizers and PSSs in a multi-machine power system by minimizing the non explicit target function. This method generally requires full system information. Kamwa *et al*. (2000) proposed a design approach for power system stabilizing controllers based on parameter optimization of compensators with generalized structures. This study has developed an effective scheme for optimizing and coordinating damping controllers under various engineering constraints emphazing those ensuring robustness to model uncertainties. Davison and Chang (1986) and Polak and Salcudean (1989) discussed about the controller tuning and coordination using decentralized design and also using constrained nondifferential optimization technique. Gibbard *et al*. (2000) discussed about the interactions occur between stabilizers in multi-machine power systems, the stabilizers being PSSs, FACTS device stabilizers or both. The interactions which are identified and quantified may enhance or degrade the damping of certain modes of rotor oscillation. Zhang and Coonick (2000) proposed a new method based on the method of inequalities for the coordinated synthesis of

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PSSs parameters in multi-machine power system in order to enhance overall system small signal stability.

Do Bomfim *et al*. (2000) presented a method that simultaneously tune multiple power system damping controllers using Genetic Algorithms. Cai and Elrich (2003) suggested the simultaneous coordinated tuning of the series FACTS Power Oscillation Damping controller in multi-machine power system. Doi and Abe (1984) developed a new coordinated synthesis method by combining eigen value sensitivity analysis and linear programming applied to the this method is used to synthesize the coordination of power system stabilizers in a new multi machine system. In this proposed study, an optimization based tuning algorithm is proposed to coordinate among multiple PSSs by both simultaneously. This algorithm optimizes the total system damping performance by means of sequential quadratic programming. In view of the study, the main objective of the present study is to systematically optimize the PSS parameters of a multi-machine power system by non-linear optimization method.

MATERIALS AND METHODS

System model: In this study, the 10-machine 39-bus power system shown in Fig. 1 is considered. Each generator of the test system is described by a two-axis fourth order model. IEEE type ST1A model excitation system has been included. System data and excitation system data are included by Padiyar (2002). Assumptions for the two-axis model and linearized equations used for the system modeling are described by Anderson and Fouad (2003). Non-linear model is linearized around an equilibrium point in order to get system model in state space form. The supplementary stabilizing signal considered is the one proportional to speed. PSS acts through the excitation system to import a component of additional damping torque proportional to speed change. It involves a transfer function consisting of a wash-out block, a lead-lag phase compensator circuit and a stabilizer gain block (Yao-Nan, 1983).

The lead-lag block provides the appropriate phase-lead characteristic to compensate the phase lag between the exciter input and the generator electrical torque. The structure of the used PSS is shown in Fig. 2. The transfer function of the PSS is given in Eq. 1:

$$\Delta V_s = K_{PSS}\left(\frac{sTw}{1+sTw}\right)\left(\frac{1+sT_1}{1+sT_2}\right)\Delta\omega \qquad (1)$$

Where:

K_{PSS} = The PSS gain
Tw = The washout time constant
T_1, T_2 = The compensator time constants

Proposed method of coordinated tuning of PSSs: Coordinated tuning of PSSs is done by non-linear optimization algorithm using the linearized system model. In this research, the parameters of each PSS controller are determined simultaneously using non-linear optimization technique. The main procedure is as follows:

- System linearization for analyzing the dominant oscillation modes of the power system
- Identification of the location of PSSs in the multi-machine power system using Relative Gain Array (RGA) method and also by Participation factor method
- Using the parameter constrained non-linear optimization to optimize the global system behavior

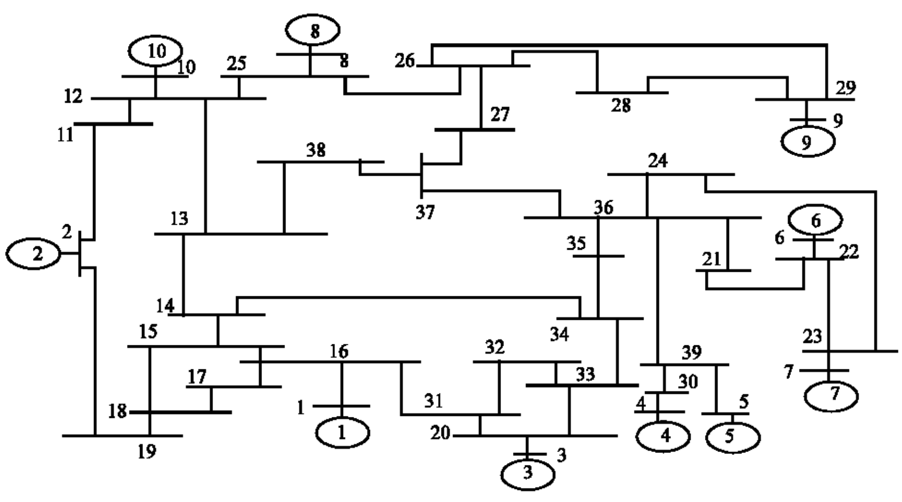

Fig. 1: New England test system (10-machine 39-bus)

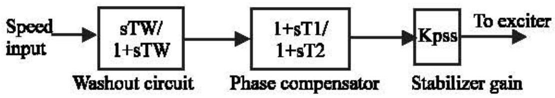

Fig. 2: Power System Stabilizer (PSS)

Detailed description of above three steps for the optimization based coordinated tuning is as follows; the total linearized system model extending the PSS is derived and can be represented as the state space model by the Eq. 2:

$$\Delta \dot{x} = A\Delta x + B\Delta u \qquad (2)$$
$$\Delta y = C\Delta x + D\Delta u$$

From Eq. 2, the eigen value, $\lambda i = \sigma_i \pm j\omega_i$, (for the critical mode i) of the total system can be evaluated. Damping ratio of the ith critical mode is given by Eq. 3:

$$\varsigma_i = \frac{-\sigma_i}{\sqrt{(\sigma^2 + \omega^2)}} \qquad (3)$$

The proposed method is to search the best parameter sets of the controllers so that a Comprehensive Damping Index (CDI) minimized. The comprehensive damping index can be represented in Eq. 4 as (Cai and Elrich, 2003):

$$CDI = \sum_{i=1}^{n}(1 - \varsigma_i) \qquad (4)$$

Where, n is the total number of dominant eigen values which include the inter-area modes (Sanchez-Gasca and Chow, 1996) and local modes. The Eq. 4 is a non-linear function in terms of PSS controller parameters. Maximization of this damping ratio (non-linear function) which is equivalent to minimization of non-linear function given in Eq. 4 in terms of PSS parameters. Optimized controller parameters for sufficient damping performance are obtained during this non-linear optimization. The main objective of this method can be very clear with the help of the Fig. 3.

Among the dominant critical swing modes, only those have damping ratio less than $\varsigma_{critical}$ are considered in the optimization. Maximization of damping ratio is carried out by moving the considered eigen values to the left hand side of the s-plane in the optimization technique. In the Fig. 3, +sign indicates eigen values before optimization. Where * sign indicates eigen values after optimization. In order to minimize the comprehensive damping index, the non-linear optimization technique implemented in Matlab optimization tool box is used. Special function from the tool box is selected for the

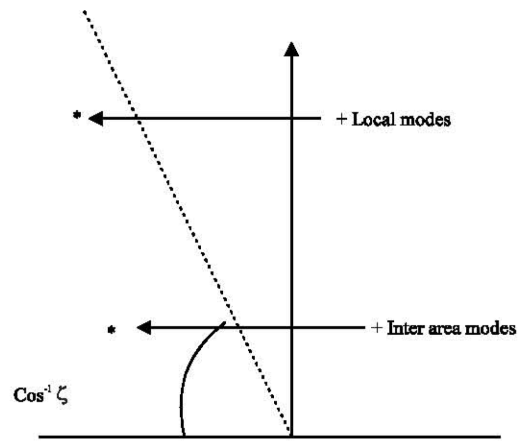

Fig. 3: Objective of optimization

minimization of non-linear programming problem. Since, the problem is a constrained non-linear optimization, this speciale function called fmincon can be used for the concerned study. The selected function finds the minimum of a non-linear multivariable function. Syntax for this function is given by Eq. 5:

$$x = \text{fmincon (fun, x0, lb, ub, options)} \qquad (5)$$

This implies optimization starts at x0 and finds the minimum x to the function i.e., objective function fun with lower bounds lb and upper bounds ub of PSS parameters to be optimized as inequality constraints. The objective of the parameter optimization can be formulated as non-linear programming problem expressed as in Eq. 6 with the constraints as in Eq. 7:

$$\text{Min. } f(z) = CDI \qquad (6)$$

Subject to the constraints:

$$E(z) = 0$$
$$F(z) \geq 0 \qquad (7)$$

Where, f(z) is the objective function defined as Eq. 4. z is a vector which consists of parameters of PSSs which are selected for tuning. In this case the parameters are PSSs gain (K_{PSS}) and phase compensator time constant T_1. E(z) is the equality functions and F(z) are the inequality functions, respectively. For the proposed method, only the inequality functions F(z) that represents the parameter constrains of each controller. The optimization starts with the pre-selected initial values of the controllers parameters indicated as vector z0. Then the non-linear algorithm is employed to adjust the parameters iteratively

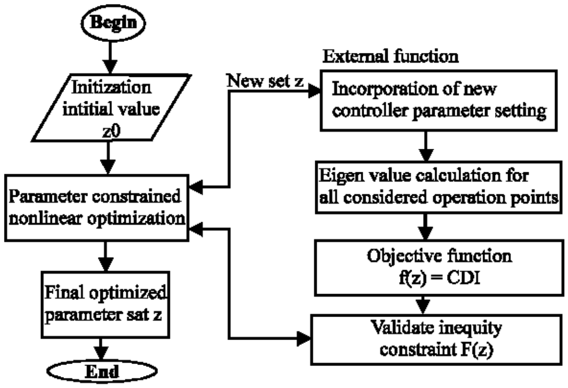

Fig. 4: Flowchart of optimization based co-ordinated tuning

until the objective function Eq. 4 is minimized. These so determined parameters are the optimal settings of PSSs controllers. This allows considering several operating points of the system simultaneously. So, the CDI is calculated for each state successively and added to the global CDI provided for the optimization algorithm. This algorithm expressed as a flowchart is shown in Fig. 4.

Simultaneous tuning algorithm: The proposed simultaneous tuning algorithm is explained as follows:

- Determine the critical modes from the rotor swing modes of the system which has the damping ratio less than $\zeta_{critical}$
- For each mode, determine the best location based on the RGA method
- The optimized parameters of the respective PSS which are connected to the highest participated machine for all the critical modes are included in the system and simulation is carried out in order to check the adequacy of damping
- If the damping is inadequate, retune the controller parameters until the sufficient damping is obtained

RESUTLS AND DISCUSSION

To evaluate the effectiveness of the proposed technique, the 10-machine 39-bus power system shown in Fig. 1 is considered. In this system, all machines are equipped with static exciters. Non-linear function fmincon is used for the optimization of the objective function of the each machine and results are taken separately. Problem is formulated as in Eq. 8:

$$\text{Min. } (1-\zeta) = 1 - \left| \frac{KPSS\ GEP(j\omega)\ (1+\omega n^2 T1^2)^{1/2}}{2\ \omega n\ M\ (1+\omega n^2 T2^2)^{1/2}} \right| \quad (8)$$

Table 1: Optimized controller parameters

Gen. no.	K_{PSS}	T_1	T_2	T_w
1	12.0432	0.0010	0.010	10
2	38.0640	0.0010	0.010	10
3	11.2791	0.0010	0.010	10
4	11.2792	0.0010	0.010	10
5	9.0056	0.0010	0.010	10
6	11.2792	0.0010	0.010	10
7	10.6075	0.0010	0.010	10
8	12.0432	0.0010	0.010	10
9	12.0432	0.0010	0.010	10
10	12.0432	0.0010	0.010	10

Table 2: Swing modes of new england test system (nominal operating condition)

Eigen values	Damping ratio	Natural frequency (Hz)
-1.0361±9.7046i	0.1062	1.5533
-0.8359±8.7394i	0.0952	1.3973
-1.0388±7.8218i	0.1317	1.2558
-1.9825±7.2774i	0.2628	1.2004
-0.5390±6.6460i	0.0808	1.0612
-0.5013±6.4141i	0.0779	1.0239
-1.0606±6.4005i	0.1635	1.0326
-0.6701±5.4632i	0.1217	0.8760
-0.7063±3.5853i	0.1933	0.5816

Subject to the constraints:

$$10 \le K_{PSS} \le 90$$

Inequality constraints:

$$0.001 \le T1 \le 1.6$$

Where:

GEP (jω) = The plant transfer function

ω_n = The natural frequency of oscillations are calculated

The optimized controller parameters using Eq. 8 for all the 10 machines are shown in Table 1. T_2 and Tw are assumed to be 0.010 and 10 sec, respectively. These optimized controller parameters are used for simultaneous tuning as well as sequential tuning. Without power system stabilizers, the system damping is poor and the system exhibits highly oscillatory response. It is therefore necessary to install one or more PSS to improve the dynamic performance. For the nominal operating condition, the critical swing modes and their corresponding damping ratio and frequency are shown in Table 2.

From the damping factors of the eigen values, it is observed that the damping of all the swing modes is unsatisfactory (ς Value is <0.4). Hence, it is required to introduce sufficient damping for each mode using PSS. To identify the optimum locations of PSS`s, the Relative Gain Array Method (RGA) (Mahabuaba and Khan, 2008). The optimal locations for the critical swing modes are found out using RGA method are shown in Table 3. The effectiveness of the simultaneous tuning procedure

Table 3: Optimum locations for swing modes

Swing mode	Optimum location
-1.0361±9.7046i	Machine III
-0.8359±8.7394i	Machine VII
-1.0388±7.8218i	Machine V
-1.9825±7.2774i	Machine VIII
-0.5390±6.6460i	Machine I
-0.5013±6.4141i	Machine X
-1.0606±6.4005i	Machine IV
-0.6701±5.4632i	Machine IX
-0.7063±3.5851i	Machine II

Table 4: Swing modes of new england test system (operating condition (a))

Eigen values	Damping ratio	Natural frequency (Hz)
-0.9652±9.7412i	0.0986	1.5580
-0.8359±8.7394i	0.0952	1.3973
-1.0388±7.8218i	0.1317	1.2558
-1.9825±7.2774i	0.2628	1.2004
-0.5390±6.6460i	0.0808	1.0612
-0.5013±6.4141i	0.0779	1.0239
-1.0606±6.4005i	0.1635	1.0326
-0.6701±5.4632i	0.1217	0.8760
-0.7063±3.5853i	0.1933	0.5816

Table 5: Swing modes of new england test system (operating condition (b))

Eigen values	Damping ratio	Natural frequency (Hz)
-0.9568±9.7649i	0.0975	1.5616
-0.8588±8.7064i	0.0982	1.3924
-0.9319±7.9825i	0.1160	1.2791
-1.7607±7.4006i	0.2315	1.2107
-0.4976±6.5604i	0.0756	1.0471
-0.5281±6.3384i	0.0830	1.0123
-0.8243±5.6254i	0.1450	0.9049
-0.7550±4.9210i	0.1516	0.7924
-0.9153±3.1249i	0.2811	0.5182

Table 6: Swing modes of new england test system (operating condition (c))

Eigen values	Damping ratio	Natural frequency (Hz)
-0.7684±11.051i	0.0694	1.7632
-0.6112±10.1157i	0.0603	1.6129
-0.8154±9.0787i	0.0895	1.4507
-1.4222±8.6217i	0.1628	1.3907
-0.5308±8.2943i	0.0639	1.3228
-0.3265±7.5605i	0.0431	1.2044
-0.2409±7.1092i	0.0339	1.1321
-0.3061±6.8213i	0.0448	1.0867
-0.2928±4.3861i	0.0666	0.6996

proposed above is investigated by carrying out simulation of the non-linear model of the sample power system for different operating condition. Optimized PSS parameters are included in the system based on the above optimum location result. PSS is connected to all the machines except the 6th machine.

Dynamic performance of the system for the nominal operating condition is obtained by giving 5° perturbation in the rotor angle as mechanical disturbance. Figure 5-13 shows the system responses for $\Delta\delta_{12}$-$\Delta\delta_{110}$ for the nominal operating condition when PSSs located in the machines as per RGA method with the 5° perturbation in the rotor angle as mechanical disturbance.

Simulation results in Fig. 5-13 shows that the effective damping performance of the optimization based tuned PSS in the 10-machine 39-bus system. The oscillations in the system with PSS are effectively damped compared with the system without PSS.

Simultaneous tuning for various operating conditions (Robustness of PSS): The robust tuning of the PSS`s is demonstrated by considering three different operating conditions. Different operating conditions taken for this practical system are:

a) Line outage (21-22) in the system
b) Line outage (21-22) and 25% load increase in the 16th and 21st bus
c) 25% generation increase in generator 7

For the above three cases, critical swing modes are found out. The critical swing modes, their corresponding damping ratios and frequency are shown as in Table 4-6.

Ranking of the damping ratio: Total 4 different operating conditions (including the nominal operating condition) are taken and all the critical swing modes are found out for all

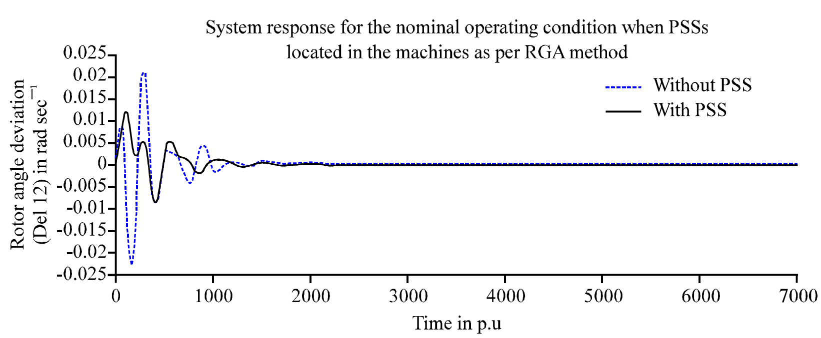

Fig. 5: System responese of the rotor angle ($\Delta\delta_{12}$) for nominal opertating condition

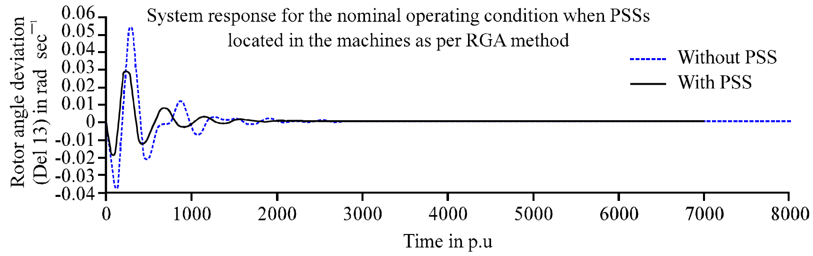

Fig. 6: System responese of the rotor angle ($\Delta\delta_{13}$) for nominal opertating condition

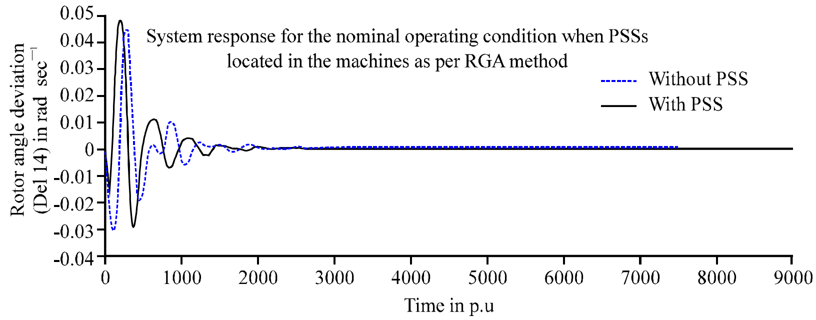

Fig. 7: System responese of the rotor angle ($\Delta\delta_{14}$) for nominal opertating condition

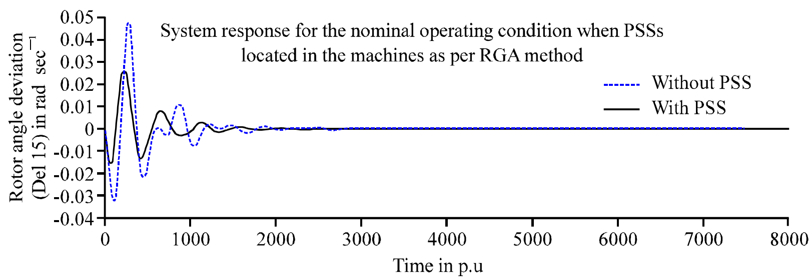

Fig. 8: System responese of the rotor angle ($\Delta\delta_{15}$) for nominal opertating condition

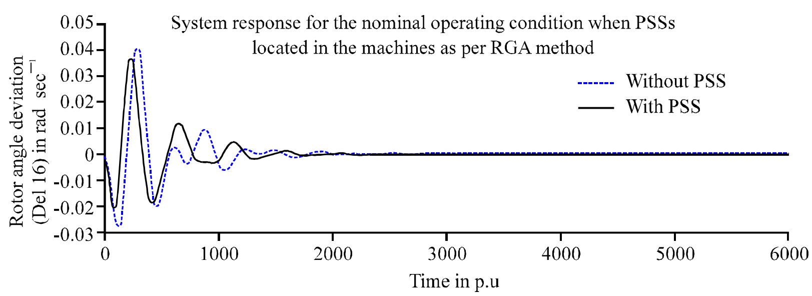

Fig. 9: System responese of the rotor angle ($\Delta\delta_{16}$) for nominal opertating condition

the four different operating conditions in the test system. After that, ranking of the swing modes are done based on the value of the damping ratios of the swing modes. For each critical mode from the damping ratios of four operating conditions i.e., nominal case, operating conditions (a-c) and lowest damping ratio is found out. The ranking is shown in Table 7. From Table 7, the lowest value of the damping ratio in each row of the Table 7 is chosen. Then from the 5th column of Table 8, the ranking of the damping ratio has been done in the ascending order of the damping ratio and arranged in ascending order of damping ratio. This is shown in Table 8. In this ranking, all selected damping ratios are of corresponding to the operating condition (c) i.e., 25%

increase in generator 7. Table 9 shows the critical modes corresponding to the damping ratios are identified after ranking. After this ranking, the optimum location for the selected modes will be done using the RGA method (Mahabuba and Khan, 2008) and also by Participation factor method (Hsu and Chen, 1987). Table 10 shows that the optimum locations of PSS`s corresponding to the critical modes after ranking of the damping ratios from the different operating conditions. In Table 11, it was revealed that the PSSs are located in all the machines except for the 5th machine.

Simulation results are taken after connecting PSSs to all the 9 machines for the operating condition-case (c). From optimized controller parameters are included in all

Table 7: Ranking of the damping ratio

Damping ratio of the critical modes of base case condition	Damping ratio of the critical modes of op. condition (1)	Damping ratio of the critical modes of op. condition (2)	Damping ratio of the critical modes of op. condition (3)	Least damping ratio from column 1-4
0.1062	0.0986	0.0975	0.0694	0.0694
0.0952	0.0952	0.0982	0.0603	0.0603
0.1317	0.1317	0.1160	0.0895	0.0895
0.2628	0.2628	0.2315	0.1628	0.1628
0.0808	0.0808	0.0756	0.0639	0.0639
0.0779	0.0779	0.0830	0.0431	0.0431
0.1635	0.1635	0.1450	0.0339	0.0339
0.1217	0.1217	0.1516	0.0448	0.0448
0.1933	0.1933	0.2811	0.0666	0.0666

Table 8: Least damping ratio

Least damping ratio from column 1-4	Least damping ratio from column 1-4 are arranged in order of the damping ratio
0.0694 (7)	0.0339
0.0603 (4)	0.0431
0.0895 (8)	0.0448
0.1628 (9)	0.0603
0.0639 (5)	0.0639
0.0431(2)	0.0666
0.0339 (1)	0.0694
0.0448 (3)	0.0895
0.0666 (6)	0.1628

Table 9: Critical modes corresponding to the damping ratios which are identified after ranking

Critical modes	Damping ratio	Operating condition
-0.2409±7.1092i	0. 0339	Case (c) i.e; 25% increase in generator no. 7
-0.3265±7.5605i	0. 0431	Case (c)
-0.3061±6.8213i	0.0448	Case (c)
-0.6112±10.1157i	0.0603	Case (c)
-0.5308±8.2943i	0.0639	Case (c)
-0.2928± 4.3861i	0.0666	Case (c)
-0.7684±11.0517i	0.0694	Case (c)
-0.8154±9.0787i	0.0895	Case (c)
-1.4222±8.6217i	0.1628	Case (c)

Table 10: Identification of the location of the machines for the placement of PSS

Critical modes	Optimum location
-0.2409±7.1092i	IX
-0.3265±7.5605i	I
-0.3061±6.8213i	X
-0.6112±10.1157i	VII
-0.5308±8.2943i	VI
-0.2928± 4.3861i	II
-0.7684±11.0517i	III
-0.8154±9.0787i	IV
-1.4222±8.6217i	VIII

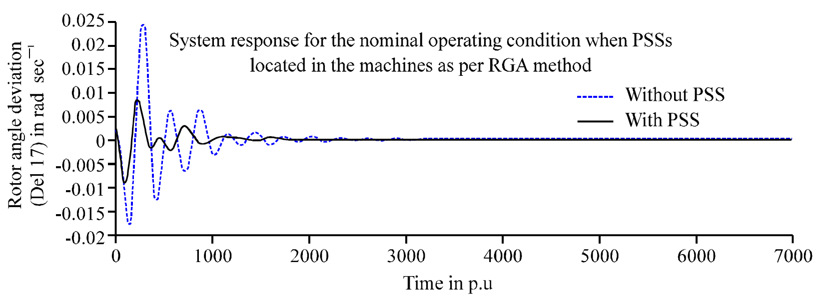

Fig. 10: System responese of the rotor angle ($\Delta\delta_{17}$) for nominal opertating condition

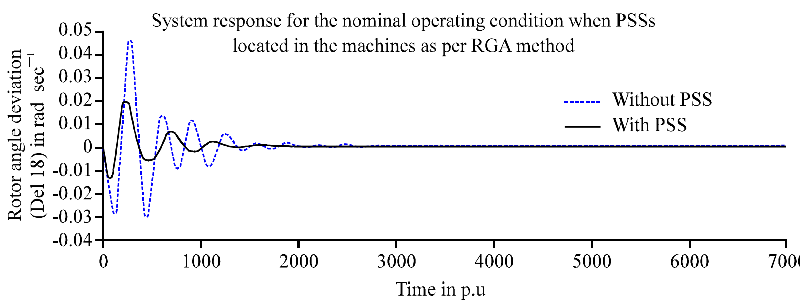

Fig. 11: System responese of the rotor angle ($\Delta\delta_{18}$) for nominal opertating condition

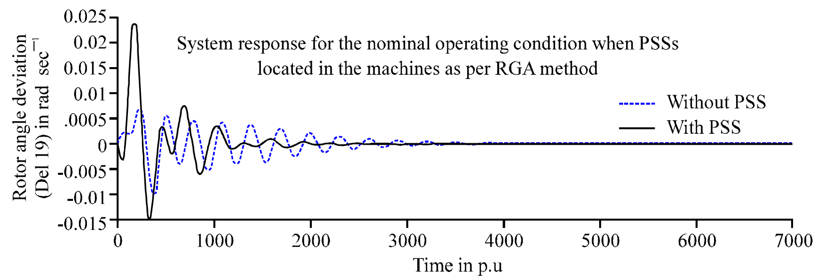

Fig. 12: System responese of the rotor angle ($\Delta\delta_{19}$) for nominal opertating condition

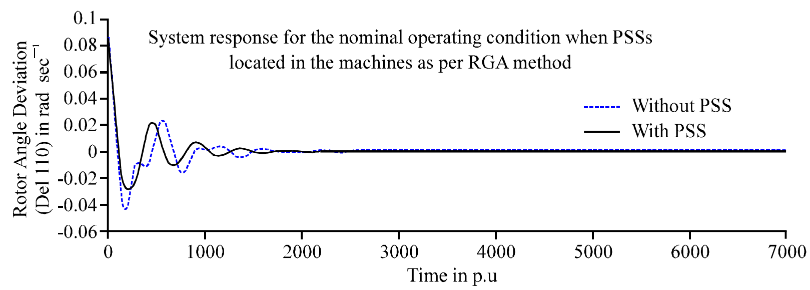

Fig. 13: System responese of the rotor angle ($\Delta\delta_{20}$) for nominal opertating condition

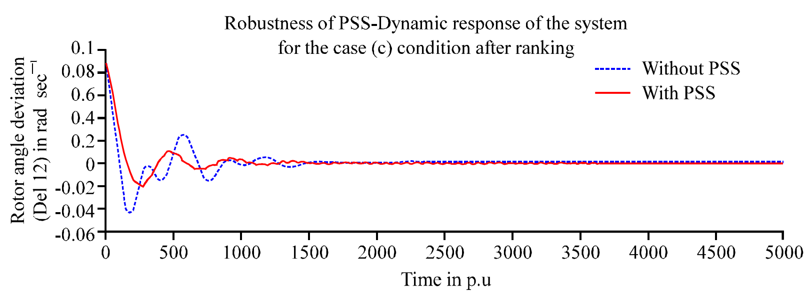

Fig. 14: Dynamic response of the system response of the rotor angle deviation ($\Delta\delta_{12}$) for opertating condition (c)

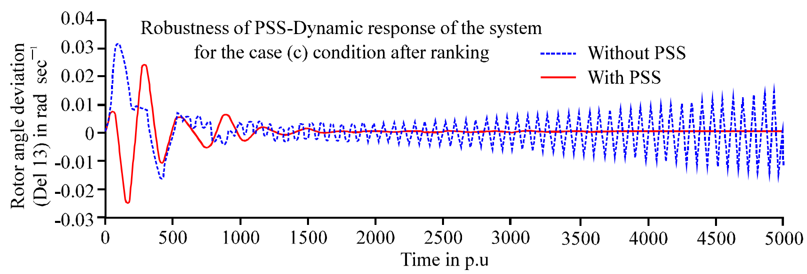

Fig. 15: Dynamic response of the system response of the rotor angle deviation ($\Delta\delta_{13}$) for opertating condition (c)

PSSs. Table 11 shows the comparison between the ratios of the critical modes before and after placement of PSSs.

Simulation results for various operating conditions: Here, also the state variable rotor angle ($\Delta\delta$) is taken for the simulation analysis. The dynamic response of the rotor angle deviation for various machines with respect to the first machine which is taken as the reference machine are shown in Fig. 14-22 shows the dynamic response of the multi machine power system for the case (c) operating

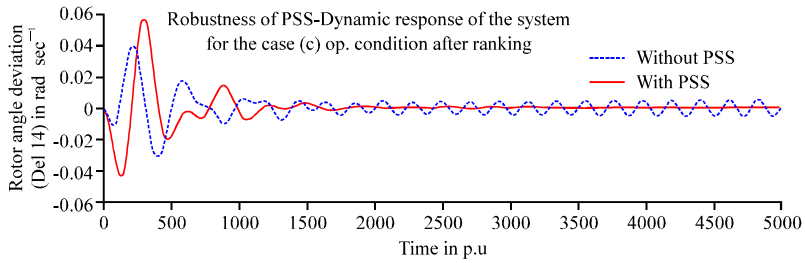

Fig. 16: Dynamic response of the system response of the rotor angle deviation ($\Delta\delta_{14}$) for opertating condition (c)

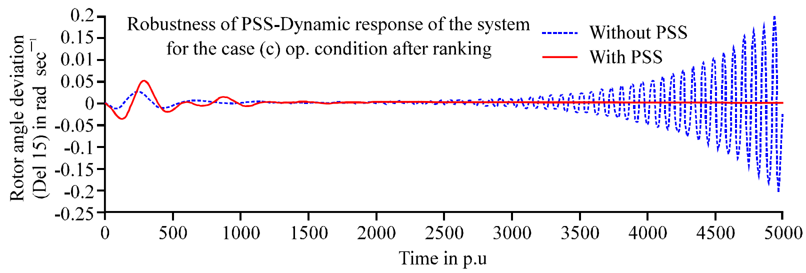

Fig. 17: Dynamic response of the system response of the rotor angle deviation ($\Delta\delta_{15}$) for opertating condition (c)

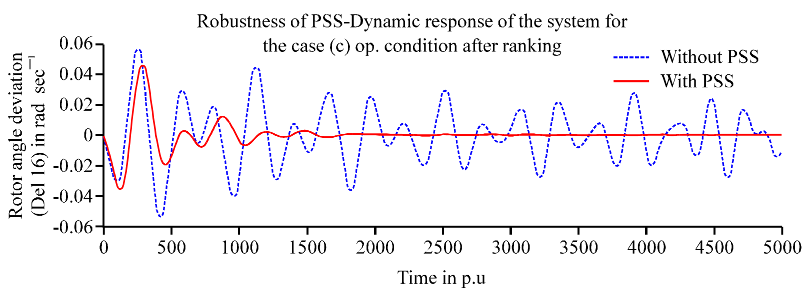

Fig. 18: Dynamic response of the system response of the rotor angle deviation ($\Delta\delta_{16}$) for opertating condition (c)

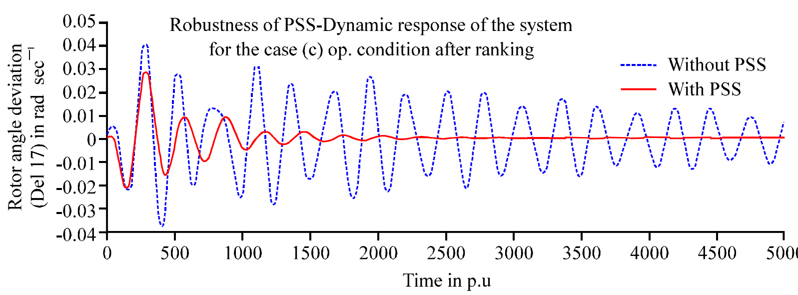

Fig. 19: Dynamic response of the system response of the rotor angle deviation ($\Delta\delta_{17}$) for opertating condition (c)

condition. This simulation results shows the robustness of the PSSs after the ranking criteria. Figure 14-22 show the responses with and without PSSs located in the corresponding machines found out as per participation factor method which is shown in Table 11. The dynamic response of the system with PSS located in all the machines except the fifth machine is shown in Fig. 14-22 for the chosen operating condition after ranking with optimized parameters of PSSs. Examining the dynamic performance, it is seen that the critical modes of oscillations are well damped. The robustness of the PSS is quiet evident. Excellent

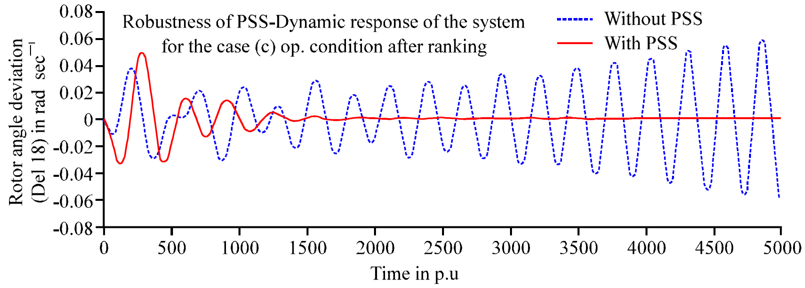

Fig. 20: Dynamic response of the system response of the rotor angle deviation ($\Delta\delta_{18}$) for opertating condition (c)

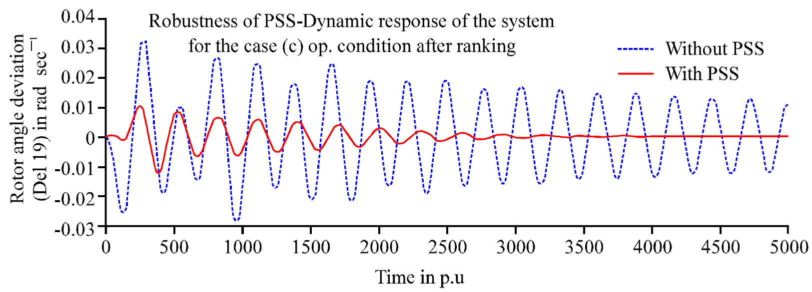

Fig. 21: Dynamic response of the system response of the rotor angle deviation ($\Delta\delta_{19}$) for opertating condition (c)

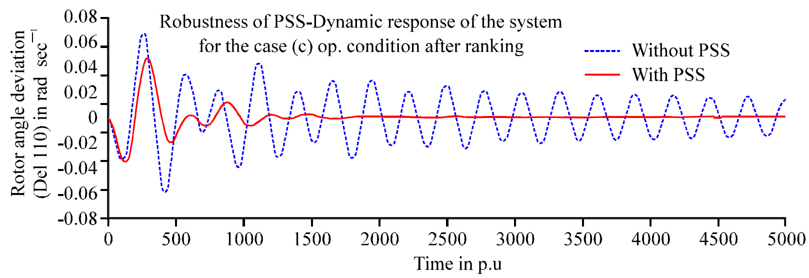

Fig. 22: Dynamic response of the system response of the rotor angle deviation ($\Delta\delta_{110}$) for opertating condition (c)

Table 11: Comparison between the damping ratios of the critical modes before and after the placement of PSS

Critical modes	Damping ratio before PSS	Damping ratio after PSS
-0.2409±7.1092i	0. 0339	0.3095
-0.3265±7.5605i	0. 0431	0.3598
-0.3061±6.8213i	0.0448	0.1040
-0.6112±10.1157i	0.0603	0.4046
-0.5308±8.2943i	0.0639	0.1481
-0.2928± 4.3861i	0.0666	0.2709
-0.7684±11.0517i	0.0694	0.3118
-0.8154±9.0787i	0.0895	0.3157
-1.4222±8.6217i	0.1628	0.3727

improvements in the damping over a wide range of operating conditions have been achieved with optimized parameters of PSS.

CONCLUSION

The proposed study mainly concerned with the optimization based co-ordinated tuning of power system stabilizers. For the optimization, non-linear programming problem is derived in terms of objective function subject to constraints for each machine.

Based on the nature of objective function, non-linear optimization function called fmincon is selected in order to determine the optimized controller parameters.

This optimization based co-ordinated tuning is applied to the 10 machine 39-bus New England system Simultaneous tuning method, a step wise procedure has been proposed in order to check the adequacy of damping for the optimized controller parameters. All the PSS parameters are tuned simultaneously for a chosen operating condition.

The results obtained for the sample system using simultaneous tuning method revealed that adequate damping could not be achieved for one of the critical mode.

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