

Optimal Tuning and Placement of Power System Stabilizers Based Eigenvalue

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Abstract

In this paper, an eigenvalue assignment based Particle Swarm Optimization and Participation Factor for Optimal tuning and placement of power system stabilizers is proposed. The proposed approach presents a two-step methodology to find optimal location and parameters of PSS. The Participation Factor method is computed using the modal analysis toolbox from DlgSILENT, and used to determine the power system stabilizers optimal location. A Particle Swarm Optimization algorithm is written in MATLAB to search the power system stabilizers optimal parameters. Two eigenvalue-based objective functions to ensure a maximum damping of the inter-area modes as well as of the local modes by assigning them in a robust stability area are considered. The performance of the proposed approach is tested and examined on the four-machine two-area power system. Linear modal analysis and non-linear time domain simulations show the robustness of the proposed approach.

Keywords: modal analysis, small-signal stability, power system stabilizers, particle swarm optimization, participation factor

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1. Introduction

With the growth of interconnected power systems, problems related to low frequency oscillation have been widely reported, causing major incidents [1]. Hence, the small signal stability improvement in particular the damping of oscillations became an important aspect to enhance power system stability. To enhance system damping, supplementary feedback stabilizing signals are introduced in the excitation systems via its automatic voltage regulator (AVR) [2]; those, will generate an electric torque component proportional to the rotor speed deviation in order to enhance system damping. As the most cost effective damping controller, power system stabilizer (PSS) has been extensively used, not only to eliminate the negative effects of automatic voltage regulator, but also to enhance the global power system oscillation damping [3]. The most important aspects for designing such a controller are their parameters tuning and the proper selection of controller's location.

It is really important to know that, in the application of PSS to increase the damping of a certain dominant mode in a multi-machine power system, the very first step is to determine the optimal location(s) for the PSS. The most effective approaches proposed are based on modal analysis of linearized system: Residues and Participation Factor [4, 5]. Recently, PSO and GA were used for the optimal location of the power system stabilizer (PSS) [6-8]. In those techniques, a list of all possible locations, is indexed by a decision variable, representing the repartition of m PSS through the N machines. However, a great simulation time is needed to solve this combinatorial problem.

Other factors such as device cost, social welfare, security criterion, land price, and environmental regulation, etc. also are important driving forces in the selection damping controller locations in a new competitive environment.

The tuning problem of power system stabilizer parameters is to find those parameters values with which the PSS will improve the damping of dominant modes and ensure a robust stability. The parameters design of conventional PSS is based on the linear control theory, which requires a nominal power system model formulated as linear, time invariant system. A lot of methods are proposed in the literature concerning the tuning problem of PSS parameters. The most of those methods are eigenvalue based on.

In [9], a sequential eigenvalue assignment algorithm for selecting the parameters of stabilizers in a multi-machine power system is proposed. In that approach, PSSs are sequentially designed to damp oscillations. Although the sequentially tuning methods are simple and have generally given satisfactory results, these methods can't ensure a global PSSs optimization, and, thus a global system optimization. The literature shows that instead of sequential optimization tuning methods, simultaneous optimization methods can be used for PSSs tuning. Heuristic methods, such as Simulated Annealing, Tabu search, and Evolutionary Algorithms (EAs), such as Genetic Algorithm (GA), Evolutionary Programming (EP), and Particle Swarm Optimization (PSO) have been applied to overcome the weakness of conventional or sequential optimization methods [10-14].

Particle Swarm Optimization (PSO) has some attractive characteristics compared to GA and other similar evolutionary techniques [15]. In [8] the optimal tuning and placement of PSS using Particle Swarm Optimization algorithm is proposed, where two eigenvalue based objective functions to enhance the damping of electromechanical modes are considered. A genuine procedure of data exchange between MATLAB and DigSILENT was developed and used to solve the optimization problem in a more convenient way. However, because the automatic state change (in or out of service) of PSS in DigSILENT for allowing the computation and evaluation of all possible location combinations while running the automatic data exchange between MATLAB and DigSILENT is quite complex, the use of PSO to address the optimal placement of PSS just allowed the computation with one PSS location; and with only one PSS, all electromechanical modes of oscillations might not shift to the robust stability area. In spite of good results of such papers, there are some shortcomings in ensuring a robust performance over a wide range of operating conditions, which increases the probability of trapping in local minima.

In this paper, an eigenvalue assignment based PSO and participation factor for optimal tuning and placement of PSS is presented which overcomes the shortcomings of previous works. Also, the multi-objective function is defined such that the PSSs will provide a robust performance for a large range of operating points. The performance of the proposed approach under different disturbances is tested and examined on the four-machine two-area power system. Linear modal analysis and non-linear time domain simulations results have been carried out to assess the robustness of the proposed approach.

This paper is organized as follows. The problem statement is given in section II. The section III proposes an approach to optimally tune and place PSSs. The simulation results are provided and analyzed in Sections IV and conclusions are given in Section V.

2. Problem Statement

This section introduces a suitable power system and PSS modeling, and the problem's objective function.

2.1. Power System Model

The Two-area test system is considered as the case study in this paper, which is specifically design to study low frequency electromechanical oscillations in large interconnected power systems [16]. A single line diagram of the system is shown in Figure 1.

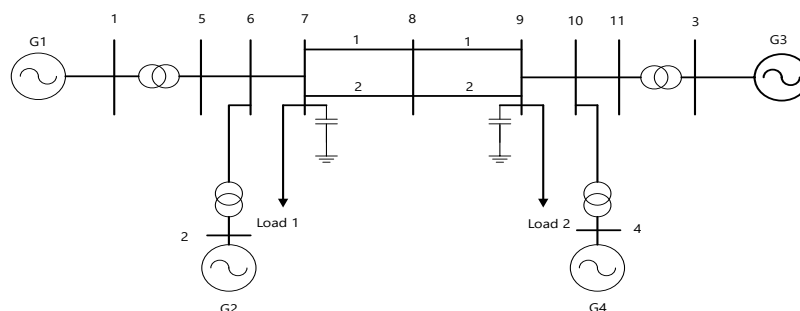


Figure 1. Single Line Diagram of Two-Area System

The power system simulator tool used for modelling and analysis of the two-area system is DigSILENT PowerFactory. All generators are equipped with identical turbine-governor system and automatic voltage regulators. The generators are defined as sixth order models and their state vector as follows:

$$X = [v_r, \theta, \psi_e, \psi_D, \psi_X, \psi_Q] \quad (1)$$

Where v_r is the rotor speed in per unit. θ is the rotor angle in radian. ψ_e, ψ_D, ψ_X and ψ_Q are the excitation flux, flux in D-winding, x-winding (second quadrature axis) and Q-winding in per unit.

The excitation system used is an IEEE model, which can be found in DigSILENT PowerFactory library as 'AVR_IEEET1', and the turbine-governor system used can be found as 'GOV_TGOV1' in DigSILENT PowerFactory.

2.2. Power System Stabilizer Structure

The PSS with a lead-lag structure of speed deviation input is considered in this study, and the structure of PSS is shown in Figure 2. It can be found in DigSILENT PowerFactory library as 'PSS_STAB1'.

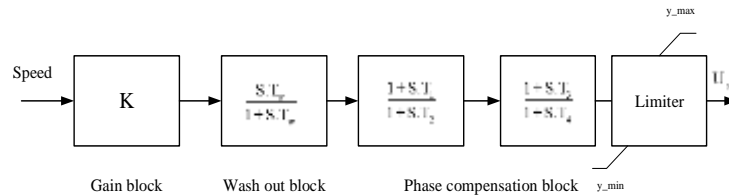


Figure 2. The Structure of PSS_STAB1

Where K is the gain in per unit. T_w is the washout integrate time constant. T_1 and T_2 are respectively the first lead/lag derivative time constant and delay time constant. T_3 and T_4 are respectively the second lead/lag derivative time constant and delay time constant. y_{min} and y_{max} are the PSS minimum and maximum limitation signals.

The tuning problem of power system stabilizer parameters is to find those parameters values with which the PSS will improve the damping of dominant modes and ensure a robust stability. A good improvement of the small signal stability has been obtained with T_w fixed at 10s [17]. And y_{min} and y_{max} are pre-specified between -0.02 and 0.1 [18].

In this paper, the parameters lower and upper bounds are chosen a large range to cover almost the possibility parameters, as follows:

$$\left. \begin{array}{l} 0.01 \leq K \leq 100 \\ 0.01 \leq T_1 \leq 3 \\ 0.01 \leq T_2 \leq 3 \\ 0.01 \leq T_3 \leq 3 \\ 0.01 \leq T_4 \leq 3 \end{array} \right\} \quad (2)$$

2.3. Objective Function

The main objective of this paper is to ensure a maximum damping of the inter-area modes as well as of the local modes by assigning all of these modes in a robust stability area. Thus the problem of optimal parameters tuning and placement of power system stabilizer (PSS) is formulated as a multi-objective optimization problem. The multi-objective function [8, 12] is formulated to optimize a set of two objective functions based on relative and absolute stability parameters which are obtained from the system eigenvalue analysis including the PSS optimally place in the system (the damping ratio and real part of eigenvalue), shown in (3).

$$J = \sum_{s_i \geq s_{cr}} [s_{cr} - s_i]^2 - a \sum_{z_i < z_{cr}} [z_{cr} - z_i]^2 \quad (3)$$

Where σ_i and ζ_i are the real part and the damping ratio of the i^{th} eigenvalue. α is the scaling factor. This multi-objective function will minimize the number of eigenvalues with real part greater or equal to the critical value σ_{cr} and with damping ratio less or equal to the critical value ζ_{cr} . This will assign all eigenvalues in a stability zone characterized by $\zeta_i \geq \zeta_{cr}$ and $\sigma_i \leq \sigma_{cr}$.

The optimization problem is to minimize J under the constraints given by equation 2, and the critical values σ_{cr} and ζ_{cr} . To ensure that the system will provide a robust performance for a large range of operating points, $\zeta_{cr} = 0.15$ and $\sigma_{cr} = -1$ values been used.

3. Proposed Approach

In this paper, to ensure that the system is small signally stable, and the PSSs will provide a robust performance for a large range of operating points, the optimal location of which generators and which PSS parameters will allow the assignment of all the eigenvalues (local and inter-area oscillations modes) in the robust stability zone D is done, and this by:

- a) First, determining the optimal PSS locations using accurate participation factor results from DigSILENT modal analysis toolbox.
- b) Then, optimizing parameters values of PSS, already installed in the system, using our PSO algorithm.

The used approach links Matlab and DigSILENT together in a genuine automatic data exchange procedure as described in [8], the test system and the controllers are modeled in DigSILENT and the PSO algorithm is implemented in Matlab. With this approach, more than one PSS can be optimized, so in order to ensure a maximum damping and optimally respect the system critical values related to the stability zone D with a minimal number of PSS, the best combination of PSS locations can be determined and 5 parameters for each PSS can be optimized.

3.2. Procedure to Compute and Analyze Participation Factor Results in DigSILENT

- a) Compute the test power system modal analysis without PSS
- b) Identify lightly damped electromechanical modes and unstable modes
- c) Compute the relative contribution of the generators speed variables in those electromechanical modes for identifying if those modes are inter-area modes or local modes
- d) Compute the participation factor associated with speed variables of each generators
- e) Identify the generators, which have the highest participation factor magnitude in each mode.

The priority is to install the PSS at the generators that has the largest participation factor to the poorest damped mode. Also, it is important to know that a PSS at a random position between the 2 generators that have the largest participation factor to a local mode will significantly influence this local mode. This concept is really important and will allow us to optimally reduce the number of PSS needed, because some generators might have a large participation factor to different lightly damped modes.

3.3. PSO and Automatic Data Exchange Implementation

In this work, the number of PSS to be optimized is flexible. For example, if the analysis of the participation factor results shows that two generators might be the optimal locations of where PSS need to be installed, we will adjust the particle size to 10, which means that the particle is simply a vector of 10 values corresponding to PSS parameters where the first 5 values are the PSS parameters for the first PSS and the 6th to 10th values are the PSS parameters for the second PSS as described in the Figure 3.

After using Participation Factor computed in DigSILENT, the automatic sequence of main data exchange can be described as follows, until the maximum number of iterations is reached:

- a) PSS parameters generated from Matlab are exported to DigSILENT.
- b) The program in DigSILENT uses and inserts those PSS parameters values into PSS designed in its interface, then, run load flow calculation, modal analysis, and calculate the system eigenvalues.
- c) The corresponding system eigenvalues are exported from DigSILENT to Matlab
- d) The PSO implemented in Matlab uses the damping ratio value and the real part value of eigenvalues to evaluate the PSSs parameters, update their values and their velocities.

During this data exchange procedure, Matlab and DigSILENT scan and change the value of a specific .CSV file after each of them finishes its work, this will ensure a reliable communication between both platforms.

When the maximum iteration number will be reached, we will easily identify our optimal PSS parameters from our PSO program and we will compute the modal analysis with them inserted at their optimal locations. If there is an electromechanical mode out of the robust stability area, we will place a PSS at the generator that influence the most this mode and run again our both program. Figure 4 shows the main steps of PSO algorithm used:

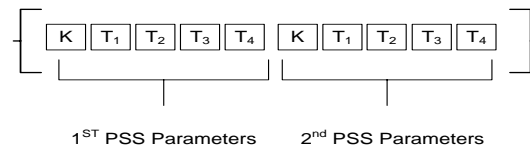


Figure 3. The Structure of a Particle

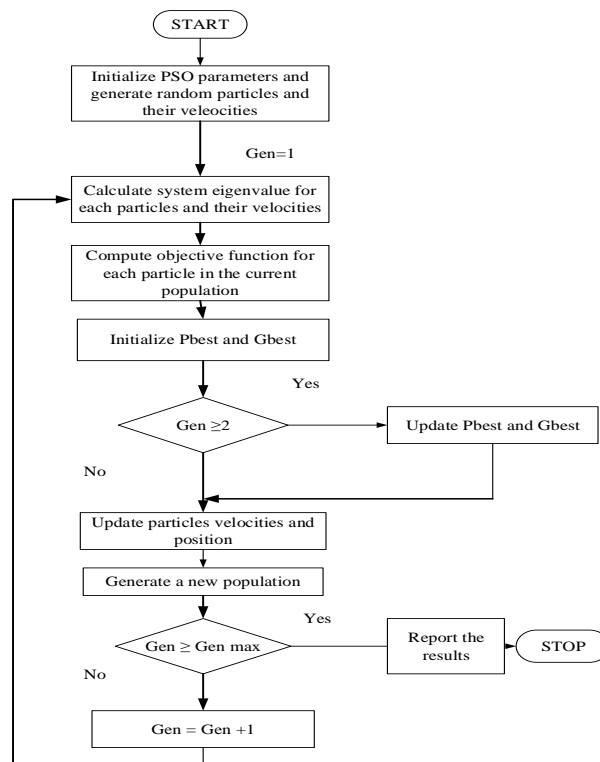


Figure 4. PSO Flow Chart

To demonstrate the effectiveness and robustness of the proposed tuning approach, three credible cases are considered. The linear modal analysis supplemented by non-linear time domain simulations is used for a complete analytical study.

4. Results and Analysis

Case 1: system without PSS

Computing modal analysis to the power system without PSS, it can be seen that the system is characterized by 3 lightly damped electromechanical modes (Ttable 1). Also, the activity of the four generators speed variables in the three lightly damped electromechanical modes (table 2) gave us more details about these modes:

- a) The local mode of oscillation 1 (1.15 Hz) in which generator from area 2 are oscillating one against the other (G_3 oscillate against G_4);
- b) The local mode of oscillation 2 (1.13 Hz) in which generator from area 1 are oscillating one against the other (G_1 oscillate against G_2);
- c) The inter-area mode of oscillation 3 (0.62 Hz) in which the generators in area 1 are swinging against the generators from area 2.

According to the damping ratio and the real part of eigenvalue of these modes it is clear that these modes are not located in the robust stability zone D. Figure 5 shows the lightly damped electromechanical modes of oscillations plot for the system without PSS.

Table 1. System Lightly Damped Electromechanical Modes of Oscillations Without PSS

Names	Damped frequency Hz	Damping ratio ζ	Eigenvalues λ
Mode 1	1.15	0.07	-0.51+j7.23
Mode 2	1.13	0.09	-0.67+j7.09
Mode 3	0.62	0.02	-0.10+j3.94

Table 2. Relative Contributions of the Three Lightly Damped Electromechanical Modes

Elements	Contribution (Magnitude/Angle)
System Mode 1	
G_1, V_f	0.131/-86.46
G_2, V_f	0.184/125.20
G_3, V_f	0.909/-179.23
G_4, V_f	1.000/0.00
System Mode 2	
G_1, V_f	0.928/176.66
G_2, V_f	1.000/-0.00
G_3, V_f	0.045/-175.46
G_4, V_f	0.016/ -85.99
System Mode 3	
G_1, V_f	0.939/175.13
G_2, V_f	0.677/178.34
G_3, V_f	1.000/-0.00
G_4, V_f	0.723/5.28

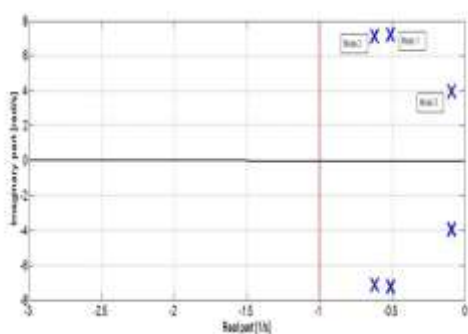


Figure 5. Lightly Damped Electromechanical Modes of Oscillations in the Complex Plane (without PSS)

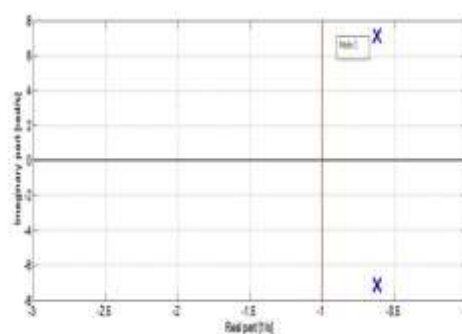


Figure 6. Lightly Damped Electromechanical Modes of Oscillations in the Complex Plane (With PSS at G_3)

The amplitudes of participation factor (Table 3) associated with speed variables of each generator for the three lightly damped electromechanical modes of oscillations show that:

In mode 1: G_3 and G_4 have the highest participation factor magnitude (G_4 has the highest magnitude with 0.63 as value and G_3 has a magnitude of 0.40).

In mode 2: G_1 and G_2 have the highest participation factor magnitude (G_2 has the highest magnitude with 1 as value and G_1 has a magnitude of 0.73).

In mode 3: G3 and G4 have the biggest participation factor (G3 has the highest magnitude with 1 as value and G4 has a magnitude of 0.65).

In a general approach, 3 potentials sites where PSS need to be installed can be considered.

The Mode 1 is a local mode and it is obvious that a PSS installed at G3 or G4 will have a significant influence on damping this mode, because these both have significant participation in this mode. The Mode 3 is the poorest damped mode and also an inter area mode. It is well known that inter area mode are the most difficult mode to control [16], thus the generator that has the largest participation factor to the mode 3 will be a first choice of where PSS have to be installed (G3). So, if a PSS at G3 can significantly influence mode 2 and mode 3, instead of installing PSS at 3 generators, only one in each area will be equipped (G2 and G3), this determination of PSS location also consider the economic criteria with 2 PSSs instead of 3 or 4 PSS.

Table 3. Participations Factor of the Three Lightly Damped Electromechanical Modes of Oscillations

Elements	Participation (Magnitude/Angle)
System Mode 1	
G ₁ , V _r	0.003/114.85
G ₂ , V _r	0.001/-145.37
G ₃ , V _r	0.403/-170.85
G ₄ , V _r	0.635/-170.81
System Mode 2	
G ₁ , V _r	0.734/-1.38
G ₂ , V _r	1.000/ 0.00
G ₃ , V _r	0.006/ 55.52
G ₄ , V _r	0.003/ -4.97
System Mode 3	
G ₁ , V _r	0.241/-42.76
G ₂ , V _r	0.125/-38.14
G ₃ , V _r	1.000/ 0.00
G ₄ , V _r	0.651/ 5.12
System Mode 1	
G ₁ , V _r	0.003/114.85
G ₂ , V _r	0.001/-145.37
G ₃ , V _r	0.403/-170.85
G ₄ , V _r	0.635/-170.81

Table 4. System Lightly Damped Electromechanical Mode of Oscillations (With PSS at G₃)

Names	Damped frequency Hz	Damping ratio ζ	Eigenvalues λ	Mode type
Mode 2	1.13	0.09	-0.67+j7,10	Local mode in area 1

Case 2: system with 1 PSS

Since all four generators considerably participate in the inter-area mode 3, G3 can be the right choice if just one PSS have to be installed in our system. In this optimization problem a population of 100 particles and 80 iterations was considered. After multiple simulations, the result indicated that for this problem, the optimal values of weighting coefficient are C1= 0.5 and C2= 0.2, and initial and final weight values are 0.9 and 0.4 respectively. A value of 10 was considered in this study for α .

After the installation of PSS at G3, we note that there is an improvement in the damping ratio and real part of eigenvalues (Table 4, Figure 6) compared to the system without PSS, but with one PSS in the system the critical values related to the stability zone D are still not respected.

Case 3: System with 2 PSS (at G₂ and G₃)

The Figure 8 and Table 3 confirmed the PSS optimal placement and shows that all electromechanical modes been shifted in the stability zone D for PSS installed at G₂ and G₃. The objective function evolution during the optimization process of 80 iterations is given in Figure 9, and shows that its final optimal value is 0.

Table 4. The Poorest Damped Electromechanical Mode of Oscillations (PSS at G_2 and G_3)

Names	Damped frequency Hz	Damping ratio ζ	Eigenvalues λ	Mode type
Mode 4	0.89	0.34	-2.08+j5.59	Inter-area mode

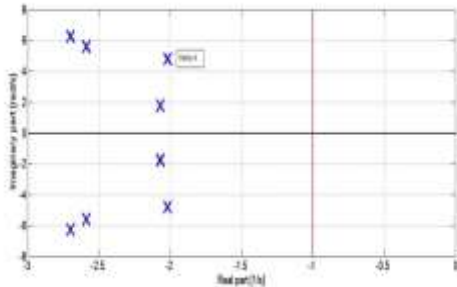


Figure 7. Electromechanical Modes of Oscillations in the Complex Plane (PSS at G_2 and G_3)

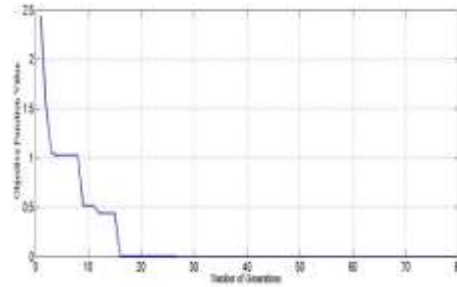


Figure 8. Objective Function Evolution

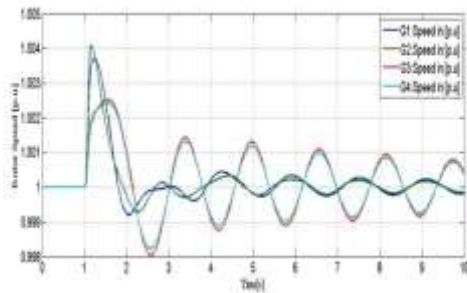


Figure 9. Generators Rotor Speeds in Per Unit Under the Three Phase Short-Circuits (System without PSS)

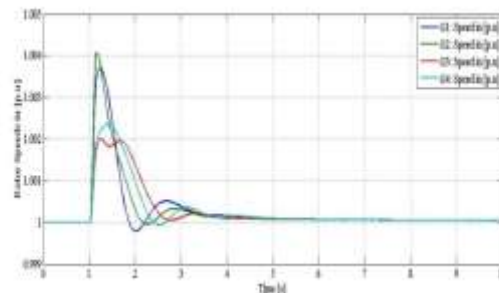


Figure 10. Generators Rotor Speeds in per unit under the Three Phase Short-Circuits (System with PSS at G_2 and G_3)

The optimal PSS placement and parameters are:

Table 5. Optimal PSS Placement and Parameters

Generators	K[pu]	T_1 [s]	T_2 [s]	T_3 [s]	T_4 [s]
G_2	14.928	0.735	2.350	2.983	0.010
G_3	11.065	2.541	0.046	1.775	2.910

In this case, the modal analysis shows that the solution obtained with 1 PSS has an advantage from an economic view point (by reducing the number of PSS) and a disadvantage by lack of robustness (lack of respect of stability criteria). Our main priority was the system stability for a wide variety of points (the robustness area D), the cost of these is not a critical issue. So the solution with 1 PSS should be less favored.

To complete the understanding of modal analysis results, time domain simulations are necessary. Thus, we will examine the stability performance of the system under a severe condition: application of a three phase short-circuits at line 7-8(1) at the simulation time $t=1$ second. The fault is cleared without tripping the line after 0.1 seconds. The generators rotors speeds response in per unit without PSS (Figure 9) shows that the settling times of generators speed response are all greater than 10 seconds but with PSS at (at G_2 and G_3) (Figure 10) the system is well damped and oscillations are quickly reduced from their appearances. The settling times of generators speed response are all lesser than 3s.

5. Conclusion

In this paper, a novel approach for optimally tune and place PSS using eigenvalue assignment based PSO and participation factor is proposed. The main feature of this method is: the simultaneous use of participation factor properties and the particle swarm optimization technique to solve the problem of ensuring a maximum damping of the inter-area modes as well as of the local modes by finding optimal PSS placement and PSS parameters allowing the assignment of eigenvalues in a robust stability area. A good interpretation of results obtained from the Participation Factor method, and the genuine procedure of data exchange between Matlab and DigSILENT allowed us to solve our optimization problem in a more convenient way. The analysis of the results shows the optimal facet of our approach.

References

- [1] Korba P. Real-time monitoring of electromechanical oscillations in power systems: first findings. *IET Generation, Transmission and Distribution*. 2007; 1(1): 80-88.
- [2] Anderson PM, Fouad AA. *Power System Control and Stability*. Ames, IA: Iowa State Univ. Press. 1977.
- [3] Larsen EV, Swann DA. Applying power system stabilizers part-I: General concepts. *IEEE Transactions on Power Apparatus and Systems*. 1981; 100(6): 3017-3024.
- [4] Yang X, Feliachi A. *Identification of optimal locations for decentralized controllers using residues*. System Theory, Twenty-Second Southeastern Symposium on. 1990: 132-136.
- [5] Ragavendiran A, Gnanadass R. *Determination of location and performance analysis of power system stabilizer based on participation factor*. Electrical, Electronics and Computer Science (SCEECS), 2012 IEEE Students' Conference on. 2012: 1-9.
- [6] Alkhatib H, Dubeau J, Choucha A, Hellal A, Arif S. *Simultaneous optimization of power system stabilizer parameters, number and location via genetic algorithms*. Universities Power Engineering Conference. UPEC 2008. 43rd International. 2008: 1-5.
- [7] Eslami M, Shareef H, Mohamed A, Khajezadeh M. *Optimal location of PSS using improved PSO with chaotic sequence*. Electrical, Control and Computer Engineering (INECCE), 2011 International conference on. 2011: 253-258.
- [8] Stativa A Gavrilas M, Stahie V. *Optimal tuning and placement of Power System Stabilizer using Particle Swarm Optimization algorithm*. Electrical and Power Engineering (EPE), 2012 International Conference and Exposition on. 2012: 242-247.
- [9] Fleming RJ, Mohan MA, Parvatisam K. Selection of Parameters of Stabilizers in Multi-machine Power Systems. *IEEE Transactions on Power Apparatus and Systems*. 1981; 100(5): 2329-2333.
- [10] Abido MA. Robust design of multi-machine power system stabilizers using simulated annealing. *IEEE Transactions on Energy Conversion*. 2000; 15(3): 297-304.
- [11] Abido MA, Abdel-Magid YL. *Robust design of multi-machine power system stabilizers using Tabu search algorithm*. IEE proceedings on generation transmission and distribution. 2000; 147(6): 387-394.
- [12] Abdel-Magid YL, Abido MA. Optimal multiobjective design of robust power system stabilizer using genetic algorithms. *IEEE Transactions on Power systems*. 2003; 17(3): 1125-1132.
- [13] Abido MA, Abdel-Magid YL. Optimal design of power-system stabilizers using evolutionary programming. *IEEE Transactions on Energy Conversion*. 2002; 17(4): 429-436.
- [14] Abido MA. Optimal design of power-system stabilizers using particle swarm optimization. *IEEE Transactions on Energy Conversion*. 2002; 17(3): 406-413.
- [15] Mondal D, Chakrabarti A, Sengupta A. *PSO Based Location and Parameter setting of Advance SVC Controller with Comparison to GA in Mitigating Small Signal Oscillations*. Energy, Automation, and Signal (ICEAS), 2011 International Conference on. 2011: 1-6.
- [16] Kundur P. *Power System Stability and Control*. New York: McGraw-Hill. 1994.
- [17] Pal B, Chaudhri B. *Robust Control in Power Systems*. Springer Science + Business Media, Inc. 2005.
- [18] IEEE Standard. 421.2-1990. *IEEE Guide for Identification, Testing and Evaluation of the Dynamic Performance of Excitation Control Systems*; 1990.