Multi-machine Power System Stabilizer Design using Sine-Cosine algorithm

Manish Verma[1,*], Khushaboo Rani Shandilya[2]

[1]*M.Tech Scholar, Department of Electrical & Electronics Engineering, Disha Institute of Management & Technology, Raipur(C.G.), India*
[2]*Assistant Professor, Department of Electrical & Electronics Engineering, Disha Institute of Management & Technology, Raipur(C.G.), India*

Abstract - : *In this paper, a sine-cosine algorithm (SCA) based design of PSS is carried out to damp out inter-area oscillations in multi-machine system. For tuning the parameters of PSS, the minimization of integral errors of rotor speed deviations is considered as objective function. The limits of parameters of conventional PSS is taken as system constraints. To test the performance of system with proposed PSS, it is compared to system with bat algorithm (BA) based PSS, system with conventional PSS and system without PSSs. The robustness of the system with proposed PSS is examined by testing the system under small-signal and large-signal instability. The proposed SCA based PSS is found to performing better than others.*

Key Words: **Inter-area oscillations; Sine-cosine algorithm; Bat algorithm; power system stabilizer; two-area four machine system.**

1. INTRODUCTION

The increase in power demand has led the expansion and interconnections of existing networks. These interconnections have various impacts on power system. One of the more pronounced phenomena in these interconnected systems is rotor angle instability [1]. Conventional power system stabilizers (PSSs) are used to damp out inter-area oscillations which occur more frequently in interconnected system. However, a proper design of PSS is required to attain such correct performance of PSSs [2].

Several reports are available which signifies the use of optimization algorithms in the design of PSS regarding power oscillation damping. In [3], the application of robust control theory to the design of electric PSS is dealt. An augmented fuzzy logic PSS for stability enhancement of multimachine power systems is presented in [4]. In [5], conventional lead-lag power system stabilizer (CPSS) is designed to damp electromechanical oscillations. In [6], the authors present the designing of Power System Stabilizer (PSS) and Static Var Compensator (SVC) based on Chaos, Particle Swarm Optimization (PSO) and Shuffled Frog Leaping (SFL) Algorithms has been presented to improve the power system stability. A step-by-step coordinated design procedure for power system stabilizers (PSSs) and automatic voltage regulators (AVRs) in a strongly coupled system is described in [7]. In [8], a new multi-objective genetic approach (MOGA) based optimization method is proposed for optimal coordinated selection of power system Stabilizers (PSS) and Flexible AC Transmission Systems (FACTS) devices. FACTS devices are containing Thyristor controlled Series Compensator (TCSC), Static var compensators (SVC), Thyristor Controlled phase shifter (TCPS) based conventional lead-lag damping controller. A new field test to adequately assess the oscillation damping effectiveness of the PSSs in a multi-generator power plant in [9]. In [10], conic programming is shown to be an effective tool to solve robust power system stabilizer (PSS) design problems, namely coordinated gain tuning and coordinated phase and gain tuning. Optimal multi-objective design of robust multimachine power system stabilizers (PSSs) using genetic algorithms is presented in [11]. A robust coordinated AVR+PSS, called the "desensitized Four Loop regulator", has been designed for the French power system and is currently being implemented [12]. In [13], a multi-objective optimization model is presented to estimate the practical stability region and maximum endurable disturbance rejection for a small-signal power system dynamic model with saturation nonlinearities and disturbance rejection. In [14], a novel evolutionary algorithm-based approach to optimal design of multimachine power-system stabilizers (PSSs) is proposed. An analysis of the performance of power system stabilizers (PSS) under different system conditions and operating loads is provided in [15]. A tabu search (TS) based power system stabilizer (PSS) is presented in [16]. In [17] a method based on Bacterial Foraging Algorithm (BFA) to simultaneously tune these modern power system stabilizers (PSSs) in multimachine power system is presented. Two classical bio-inspired algorithms, which are small-population-based particle swarm optimization (SPPSO) and bacterial foraging algorithm (BFA), are presented in [18] for the simultaneous design of multiple optimal PSSs in two power systems. A method for PSS parameter tuning. The proposed method is based on the system identification using a Kalman filter is proposed in [19]. In [20], a modified particle swarm optimization (PSO) algorithm with a small population is presented for the design of optimal PSSs. Application of artificial neural network (ANN) in the design of an adaptive power system stabilizer is presented in [21]. A pole placement technique for power system stabilizer (PSS) and thyristor controlled series capacitor (TCSC) based stabilizer using simulated annealing (SA) algorithm is presented in [22]. Optimal locations and design of robust multimachine power system stabilizers (PSSs) using genetic algorithm (GA) is presented in [23]. A new metaheuristic method, the BAT search algorithm based on the echolocation behavior of bats is proposed in [24] for optimal design of Power System Stabilizers (PSSs) in a multimachine environment. Cuckoo Search (CS) algorithm is introduced in [25] for optimal Power System Stabilizers (PSSs) design in a multimachine power system. BFOA-based power system stabilizer (PSS) for the suppression of oscillations in power systems is proposed in [26]. In [27], the design of fuzzy logic power system stabilizer (FPSS) is carried out using a harmony search algorithm (HSA) to optimize the input–output scaling factors of the fuzzy logic controller. The tuning of the PSS parameters for a multi-machine power system is usually formulated as an objective function with constraints consisting of the damping factor and damping ratio in [28].

In this work, a sine-cosine algorithm (SCA) based design of PSS is carried out to damp out inter-area oscillations in multi-machine system. SCA is one of recent powerful optimization algorithm [29]. For tuning the parameters of PSS, the minimization of integral errors of rotor speed deviations is considered as objective function. The limits of parameters of conventional PSS is taken as system constraints. To test the performance of system with proposed PSS, it is compared to system with bat algorithm (BA) based PSS, system with conventional PSS and system without PSSs. The robustness of the system with proposed PSS is examined by testing the system under small-signal and large-signal instability. The proposed SCA based PSS is found to performing better than others.

2. STRUCTURE OF PSS

The classical phase compensation approach is used in this thesis. The block diagram of classical lead-lag PSS is shown in Fig. 1. It consists of a gain block, washout circuit, phase compensation block and a limiter. The major objective of providing PSS is to increase the power transfer in the network, which would otherwise be limited by oscillatory instability. The PSS must also function properly, when the system is subjected to large disturbances.

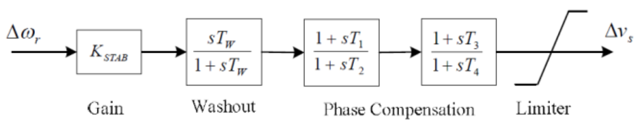


Fig -1: Block diagram of classical PSS.

3. SYSTEM UNDER STUDY

A widely used two-area four machine Kundur's test system is studied in this work. MATLAB model of the system is developed as shown in Fig. 2. The test system consists of two fully symmetrical areas linked together by two 230 kV lines of 220 km length. It was specifically designed in [30, 31] to study low frequency electromechanical oscillations in large interconnected power systems. Each area is equipped with two identical round rotor generators rated 20 kV/900 MVA. The synchronous machines have identical parameters [30, 31], except for inertias which are H = 6.5s in area 1 and H = 6.175s in area 2 [30]. Thermal plants having identical speed regulators are further assumed at all locations, in addition to fast static exciters with a 200 gain [30, 31]. The load is represented as constant impedances and split between the areas in such a way that area 1 is exporting 413MW to area 2. Transmission and generation losses may vary depending on the detail level in line and generator representation.

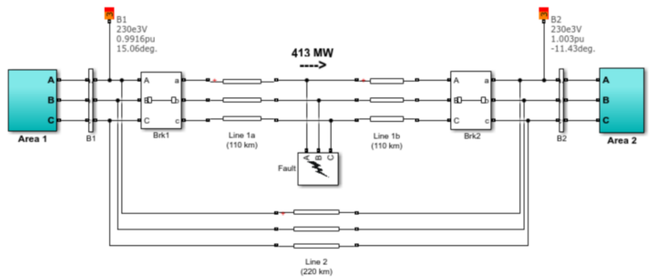


Fig -2: Simulink model of studied system

4. PROBLEM FORMULATION

For tuning the parameters of PSS, the minimization of integral time-multiplied absolute errors (ITAE) of the speed deviations of the generators of the system is considered as the objective function. Mathematically, the objective function J is expressed in the following manner:

$$J = \int_{t=0}^{T_{sim}} \left(\Delta\omega_i \right) \cdot t \cdot dt$$

where, $\Delta\omega_i$ is the speed deviation od ith generator and $i = 1, 2, 3, 4$. T_{sim} is the total simulation time. The objective function J defined in (1) is minimized subject to constraints posed the parameters of the PSS. The constraints are defined as follows:

$$K_{STAB}^{\min} \le K_{STAB} \le K_{STAB}^{\max}$$

$$T_1^{\min} \le T_1 \le T_1^{\max}$$

$$T_2^{\min} \le T_2 \le T_2^{\max}$$

$$T_3^{\min} \le T_3 \le T_3^{\max}$$

$$T_4^{\min} \le T_4 \le T_4^{\max}$$

where, K_{STAB} is the gain of PSS and T_1, T_2, T_3, T_4 are the coefficients of phase compensation block of PSS. '$\min$' and '$\max$' superscripts represent minimum and maximum values of the parameters, respectively.

Therefore, the prime task of tuning parameters of PSS is accomplished by minimizing the objective function J defined in (1) subject to the system constraints defined in (2), (3), (4), (5), and (6). In this work, sine-cosine algorithm (SCA) is proposed to solve the problem of tuning of parameters of PSS.

5. SINE-COSINE ALGORITHM

5.1 Overview of SCA

SCA is a population based newly developed optimization algorithm [29]. The algorithm is population based in which it starts with a random set of solutions/search agents positioned randomly in the search space of an optimization problem. The search agents are guided toward an optimal point/solution in the search space via a fitness function that evaluate each search agent in each iteration of the algorithm. SCA maintains a population of m search agents and each agent is represent by n dimensions decision variable vector $X_i = (x_{i1}, x_{i2}, \cdots, x_{in})$ where X_i is the ith search agent in the population. In addition, the algorithm keep track of the best solution's position P achieved by all search agents in the population at each iteration. The mathematical model used in the SCA algorithm is based on the following update function for any search agent X_i:

$$x_{ij}^{t+1} = \begin{cases} x_{ij}^t + r_1 \cdot \sin(r_2) \cdot \left| r_3 P_j^t - x_{ij}^t \right| & \text{if} \quad s < 0.5 \\ x_{ij}^t + r_1 \cdot \cos(r_2) \cdot \left| r_3 P_j^t - x_{ij}^t \right| & \text{if} \quad s \geq 0.5 \end{cases} \tag{7}$$

$$r_1 = a - t \frac{a}{T_{\max}} \tag{8}$$

where t is current iteration number, and r_1 is a control parameter that balance the exploration and exploitation phases of the algorithm which decreases linearly from a constant value a to 0 by each iteration according to (8). Each of r_2, r_3 and s are random numbers.

This model has a circular search pattern in which the best solution or the desired destination point is in the center of a circle and the search agent is positioned around it. The circular search region is divided into subregions that represent possible exploration regions for X_i. Parameter r_1 value controls how X_i move into such regions. If $r_1 > 1$ then X_i move towards P i.e exploitation step otherwise it move away from P i.e. exploration step. Moreover, r_1 is used in the context to balance the exploration and exploitations steps since it decreases linearly according to (8). Random value of r_2 control how far X_i move along its direction according to r_1, r_2 assign random weights to the best solution P to stochastically emphasize when $r_3 > 1$ or deemphasize when $r_3 < 1$ the desalination in defining the distance. Parameter s randomly switch between the sine and cosine parts of (7).

5.2 Implementation of SCA to the problem

SCA is applied to solve the problem of tuning parameters of PSSs. The various steps involved in their implementation are summarized below:

Step1: Read system data and control parameters of algorithms i.e. population size, maximum number of iterations and boundary conditions.

Step 2: Generate initial population of solution randomly within search space.

Step 3: Evaluate objective function and identify best solution.

Step 4: Update the solution according updating equation.

Step 5: Select better solutions to take part in next iteration

Step 6: Go to step 3 until any termination criterion is met.

6. SIMULATION RESULTS AND DISCUSSION

In this chapter, the simulation results and discussion are presented. For simulation, two test cases of small-signal stability and large signal stability are considered. The studied system is two-area four machine system. SCA algorithm is applied to tune the parameters of power system stabilizers. A total of 100 iterations and a population size of 20 is considered for all test cases. The modelling of the system and implementation of the algorithms are done on MATLAB platform. SCA has and added advantage of being algorithm-specific parameters less. For BA, the parameters considered for the simulation are $f_{\max} = 2$, $f_{\min} = 0$, $\alpha = 0.5$, $\gamma = 0.5$ and $r = 0.01$. The range of parameters of PSS are tabulated in Table 1.

Table-1: Range of parameters of PSS

Parameters	K_{STAB}	T_1	T_2	T_3	T_4
Range	1 - 50	0.01– 0.01	0.01- 0.1	1- 10	1- 10

Two test cases are considered for proper tuning of parameters of PSS. First case tests the robustness of proposed PSS under small-signal stability. Second case tests the performance of proposed PSS for large-signal stability. In both the cases, the tuned parameters along with value of objective function is tabulated for SCA based PSS and compared with BA based PSS. Time-domain simulations are presented to illustrate the better performance of the system with proposed PSSs.

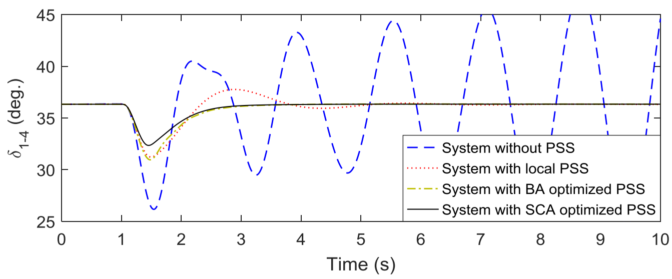
6.1 Small-signal stability

To demonstrate the performance of proposed PSS, small-signal stability assessment of the system is performed. An increase of 5% in voltage reference of generator G1 is considered which is applied at 1 s and continued for 0.2 s. Under this case, the parameters of the PSS are tuned using SCA and BA. The results are tabulated in Table 2. From the table it can be seen that the minimum value of objective function J is found to be **8.3767e-04** which is obtained from SCA. Therefore, it can be said that SCA based PSS is better in performance than BA based PSS.

Table-2: Tuned parameters for case of small-signal stability

Values	BA based PSS	SCA based PSS
J	11.9040e-04	**8.3767e-04**
K_{STAB}	36.8333	49.4111
T_1	0.0100	0.0749
T_2	0.0100	0.0278
T_3	7.1173	6.1905
T_4	4.8602	5.2398

Time-domain simulations are presented to show the performance of proposed PSS in comparison to the system without PSSs and system with local PSSs only. Fig. 3 shows the difference of rotor-angles of generator G1, G2 and G3 with generator G4. From the figures, it can be inferred that the system with proposed PSS is better in performance that system with BA optimized PSS and the system with local PSSs only and the system without PSSs. Fig. 4 shows the power flow in line B1-B2. From this figure, the superiority of proposed SCA based PSS is confirmed. Further, the rotor speed deviations of different generators are shown in Fig. 5. The figure suggests that the system with proposed PSSs are performing well than others.



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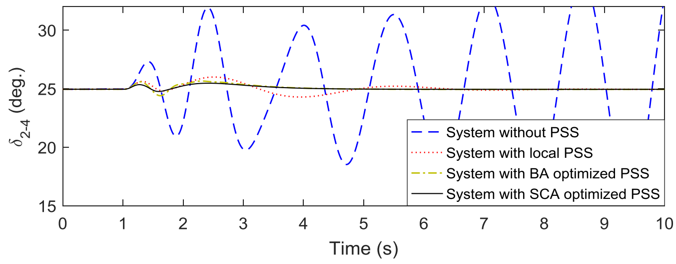

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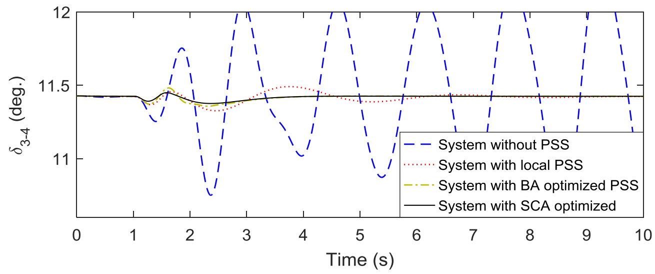

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Fig -3: Rotor-angle deviations for case of small-signal stability

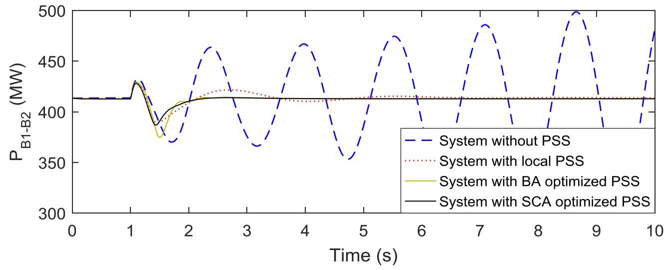
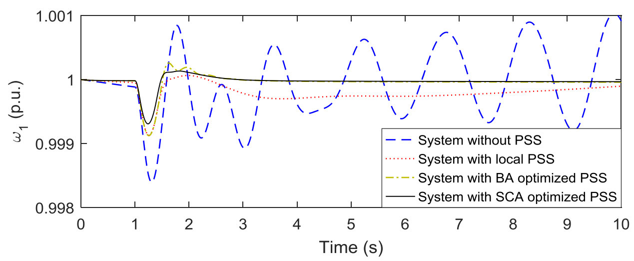


Fig -4: Power flow in line B1-B2 for case of small-signal stability



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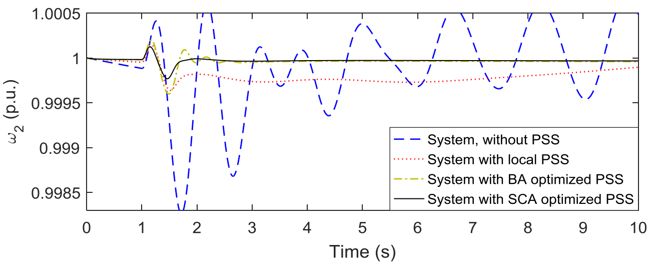

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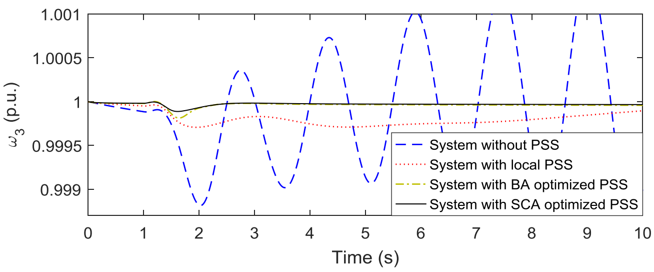

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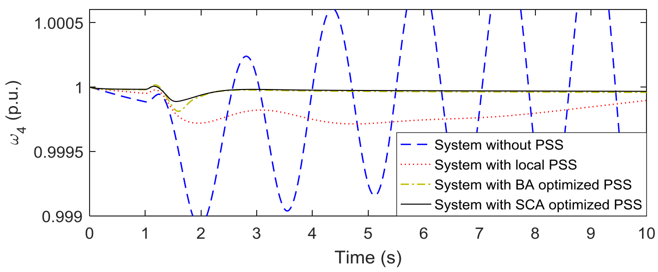

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Fig -5: Rotor speed deviations for case of small-signal stability

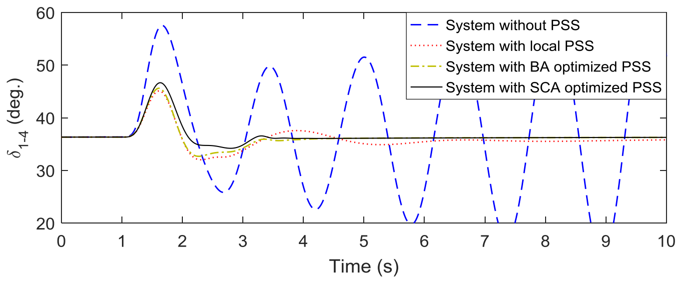
6.2 Large-signal stability

In this case, the performance of proposed PSS is examined for occurrence of any large disturbances in the system. For simulation, a three-phase to ground fault is initiated on the middle of the line B1-B2 at 1 s and cleared after 0.1 s. Under this case, the parameters of the PSS are tuned using SCA and BA. The results are tabulated in Table 3. From the table it can be seen that the minimum value of objective function J is found to be **0.0057** which is obtained from SCA. Therefore, it can be said that SCA based PSS is better in performance than BA based PSS.

Time-domain simulations are presented to show the performance of proposed PSS in comparison to the system without PSSs and system with local PSSs only. Fig. 6 shows the difference of rotor-angles of generator G1, G2 and G3 with generator G4. From the figures, it can be inferred that the system with proposed PSS is better in performance that system with BA optimized PSS and the system with local PSSs only and the system without PSSs. Fig. 7 shows the power flow in line B1-B2. From this figure, the superiority of proposed SCA based PSS is confirmed. Further, the rotor speed deviations of different generators are shown in Fig. 8. The figure suggests that the system with proposed PSSs are performing well than others.

Table 3. Tuned parameters for case of large-signal stability

Values	BA based PSS	SCA based PSS
J	0.0059	0.0057
K_{STAB}	40.6172	31.6720
T_1	0.0954	0.0209
T_2	0.0792	0.0145
T_3	8.9585	5.8474
T_4	7.7384	2.8762



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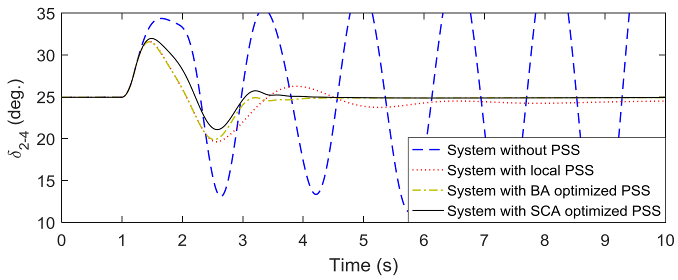

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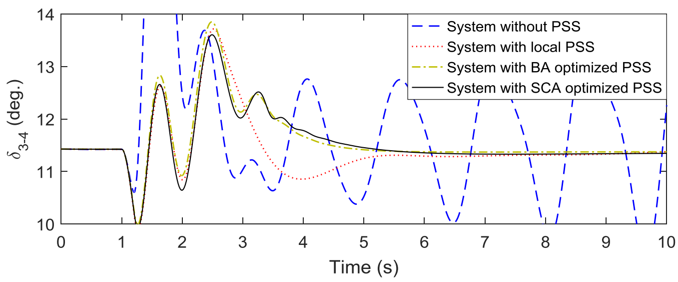

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Fig -6: Rotor angle deviations for case of large-signal stability

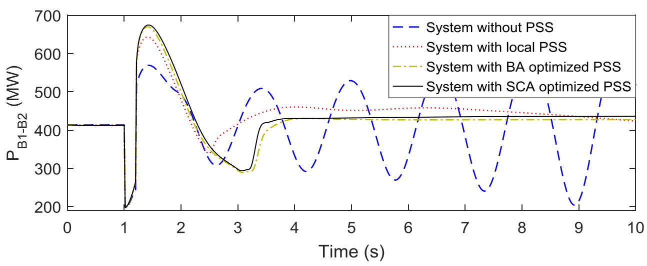
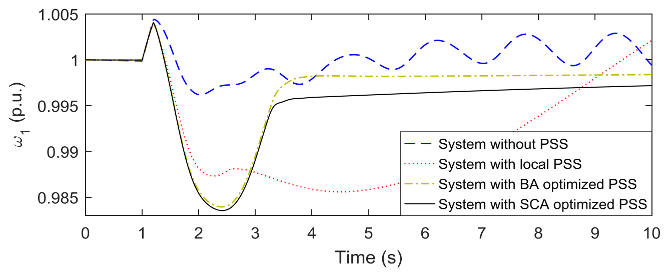


Fig -7: Power flow in line B1-B2 for case of large-signal stability



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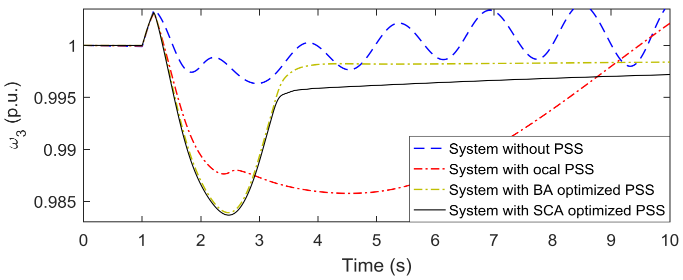

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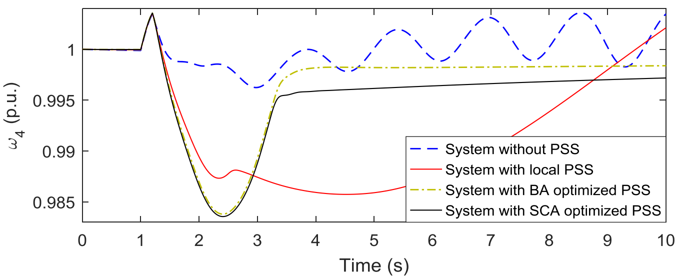

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Fig -8: Rotor speed deviations for case of large-signal stability

7. CONCLUSION

In this work, the tuning of parameters of PSS is carried out by sine-cosine algorithm (SCA) in order to design a proper PSS for power oscillation damping. A widely used two-area four machine test system is utilized for simulation. SCA based PSS is designed by minimizing integral errors of rotor speed deviations. Two test cases of small-signal and large-signal stability assessment is carried out to test the performance of proposed SCA based PSS. The performance of proposed PSS is compared with BA based PSS and the results approve the superior performance of the proposed PSS. The system with proposed PSS is compared with system with local PSS only and the system without PSS and it can be concluded from the observations that the system with proposed PSS are performing better than system with local PSSs and system without PSSs. Future research directions are a hybrid optimization algorithm can be applied to tune the parameters of PSS so as to get better tuned values, a multi-objective optimization problem can be formulated in order to achieve better performance of the system under disturbances, design of PSS for renewable integrated energy system can be performed with proposed technique and the performance of the proposed PSS can be tested for large power system.

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