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Optimal Design of PSS Using an Improved Differential Evolution Algorithm for Inter-Area Oscillation Damping

Mohsen Saniei, Bahram Noshad

Shahid Chamran University (SCU), Ahvaz, Iran

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ABSTRACT

In this paper, the parameters of a power system stabiliser (PSS) with help of a combination of a Differential Evolution algorithm (DE) and Local Search Algorithm (called the DELSA (Memetic DE algorithm)) are introduced, which are designed independently, converge to the correct and optimal solution in a small number of iterations and are attuned to damp low frequency oscillations, such as local mode oscillations, inter-area mode oscillations. In this paper, the DELSA algorithm searches in a wide-ranging area which probably has the optimal solution. In this paper, the three-area power system is simulated in the time domain. Simulation is done by MATLAB program.

KEYWORDS*:* Differential Evolution Algorithm (DE), Inter-area Oscillations, Local Search (LS), Memetic DE Algorithm, PSS, Small Signal Stability.

List of symbols

i, j	Index for bus
PG_i^{con}	Contracted real power generation at bus i, p.u.
$XP_{i,gen}$	Actual real power transaction between load at bus i and generators, *gen*
Q_i	Reactive power support at bus i, p.u
QD_i	Reactive power demand at bus i, p.u
QC_i	Reactive support from shunt capacitors at bus i in per unit;
θ_{ij}	Angle associated with , radians
Y_{ij}	Element of network and admittance matrix, p.u
V	Voltage at a bus in per unit
δ	Voltage angle, radians.
$W_{k,i}$	Binary variable
a_0	Availability price offer.
m_1	Operating price offer for operating in under-excited mode (absorb reactive power), $Q_{Min} \le Q \le 0$, \$/MVArh.
m_2	Operating price offer for operating in the region $Q_{base} \le Q \le Q_A$, \$/MVArh.
$m_3 Q$	Opportunity price offer for operating in region $Q_A \le Q \le Q_B$, \$/MVArh/MVArh.
VSM	Voltage Stability Margin
ρ_0	The uniform availability price
ρ_1 - ρ_2	The uniform cost of loss prices
ρ_3	The uniform opportunity price

Corresponding Author: Bahram Noshad, Shahid Chamran University (SCU), Ahvaz, Iran.
E-mail addresses: bahramnoshad@yahoo.com

1. INTRODUCTION

Small disturbances are caused by low frequency oscillations (LFO) in large scale multi-area power systems. In general, these power systems are connected with weak tie lines. Usually, local modes are controlled and damped by a power system stabiliser (PSS). Until now, all controller design methods, such as nonlinear, adaptive, multi-variable, optimal, robust [1, 2], fuzzy systems, neural networks and combinations of these methods [3], have been in use for PSS parameter design. In recent times, heuristic techniques based on search and evolution, such as genetic algorithms (GA) [4], particle swarm optimisation (PSO) [5], ant colony, memetic [6], Tabu search [7], and artificial immune algorithm (AIA), have been utilised. Results with these techniques are better than those with previous techniques. Among these, the genetic algorithm and AIA are most noteworthy. In this paper, analysis of dynamic stability for a three-area power system was performed in the time domain with non-linearity. The instability growth of the rotor angle due to the lack of synchronisation torque and increasing rotor oscillation due to the lack of damping torque lead to instability and inter-area oscillation (influence weak damping). In order to limit these oscillations, PSS with optimal and coordinated parameters designed by the DE algorithm and LSA, were used. Both of these algorithms are versions of a meta-heuristic algorithm [8, 9]. DE and LSA are called Memetic DE. Simulation outcomes show that with coordinated modification of PSS parameters by using the projected method, oscillations are damped more quickly than by other heuristic methods, and the system has a reliable stability.

II. Power System Modelling

The main duty of PSS is to improve the damping of generator rotor oscillations by controlling the excitation circuit with the use of additional stabilising signals [10, 11]. In this paper, the general structure of the power system stabiliser consists of two lead-lag blocks: a washout block and a gain block. Fig. 1 shows these blocks with the excitation system diagram.

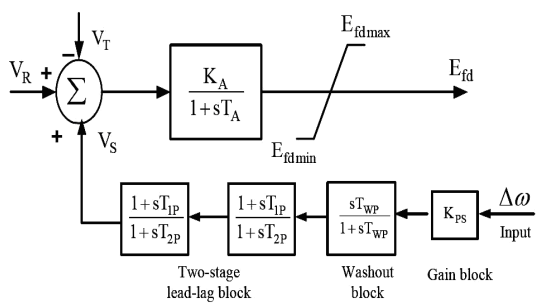

Fig.1: PSS, model IEEE-PSS1A, Input: variation of speeds with block diagram of excitation of system

In Fig 1, K_{ps} is the gain acted on frequency error and increases it. The washout block is a differentiator and only allows the variations to pass. This block removes the permanent part of the signal. The amount of T_{wp} is selected to be as large as needed. After designing Ts, the last step is determined the value of K_{ps}. In practice, because of the limitations and nonlinearity of the system, K_{ps} cannot be selected to be as large as needed. The optimal value of this factor can be obtained by simulation and trial and error [12, 13]. The proposed power system is a three-area power system that it was simulated in MATLAB program. If a disturbance is introduced into a multi machine power system (in stability analysis), the frequency, load angle and voltage of all units will changes. Usually the frequencies of these oscillations are from a 10th of a hertz to several hertz. These oscillations called low frequency oscillations (LFO). The LFO is divided into two modes: the first is the local mode (1-3 Hz), and the other is the inter-area mode (0.1-1 Hz). In a synchronous generator, the main reason for oscillations is the opposition of mechanical and electrical torques. Mechanical torque is applied to the rotor by a turbine of a generator, and electrical torque is applied by the winding of a stator. The effect of the excitation field on the LFO is positive, and this effect can reduce the overshoot and settling time. The AVR loop attenuates damping torque, and hence, the LFO time increases. To control the bus voltage, the AVR loop is necessary, so power system stabilisers are used to compensate the negative effect on the LFO. Thus, the PSS must be designed such that the torque applied to the rotor of the generator is in-phase with the angular velocity [14].

III. Differential Evolution Algorithm (DE)

The differential evolution algorithm was introduced by Storn and Price in 1996 [15]. The DE algorithm is an initial population of solution vectors updates sequentially. The DE algorithm uses sum/subtraction operators and other operators and is a stochastic, population-based optimisation algorithm. It was developed to optimise real (float) parameters of a real valued function. The DE algorithm is a simple and reliable method.

a) Initial population: the DE algorithm starts with making an initial population of individuals NP rows and D columns.

b) Mutation: In this step, the DE algorithm generates an offspring vector for each parent.

c) Boundary check or Mapping: If there is needed, an offspring vector must be in [Lo, Hi].

d) Crossover: In this step, the mutated vector and initial population vector generate test vectors.

e) Selection–Offspring are compared to the parents, and the DE algorithm generates the population of the next generation.

After the selection step, the calculation cycle in the DE algorithm continues to converge all of the vectors (until DE Algorithm receives a stop (end) condition). The general flowchart of the DE algorithm is shown in Fig. 2. For mutation, the DE algorithm is divided into 5 strategies: Best/rand strategy, Old/best/rand strategy, Best/rand/rand strategy, Rand/rand strategy and Rand/rand/rand strategy. In the first three methods, the next generation is generated from the best parents and the differentiation of random vectors, but in the two other methods, the next generation is generated from only random differential vectors. In this paper, the VSHDE (or the DE algorithm with a variable SCALE factor) algorithm is used with the best/rand/rand strategy, and within q iterations the factor F in this algorithm is modified as follows:

$$F_t + 1 = \{c_d * F_t \quad \text{if} \quad P_{st} < 1$$
$$C_i * F_t \quad \text{if} \quad P_{st} > 1 \qquad (1)$$
$$F_t \quad \text{if} \quad P_{st} = 1\}$$

Where $C_d = 0.82$ and $C_i = 1/0.82$ are constant values and P_{st} represents the number of successful mutations (the number of offspring that have better values than their parents). This step will perform after the selection step, and the parameters are adjusted as:

$$Np = 5 \quad , \quad F = 1.2 \quad , \quad q = 10$$

The algorithm begins with NP solution vectors chosen randomly. For each *i* in $(1,...,NP)$, a 'mutant vector' is calculated as

$$V_i = X_{r1} + F.(X_{r2} - X_{r3}) \qquad (2)$$

where r_1, r_2 , and r_3 are mutually distinct and drawn randomly. The indices are $(1,...,NP)$, and $0 < F <= 2$. Fig. 3 shows the generation of the mutated vector V_i in the DE algorithm.

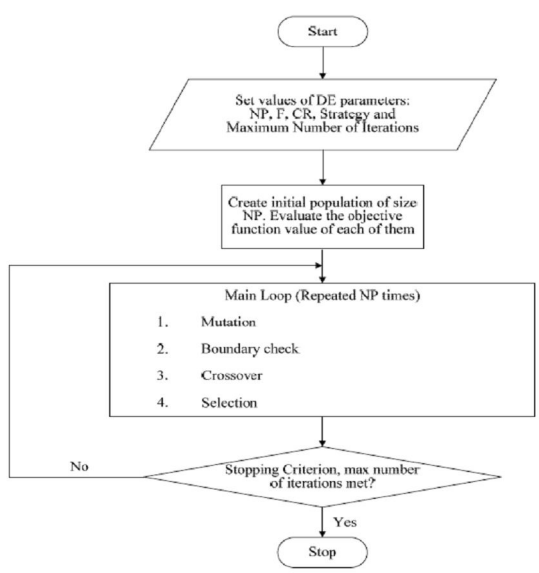

Fig. 2: Differential Evolution Algorithm flowchart [16]

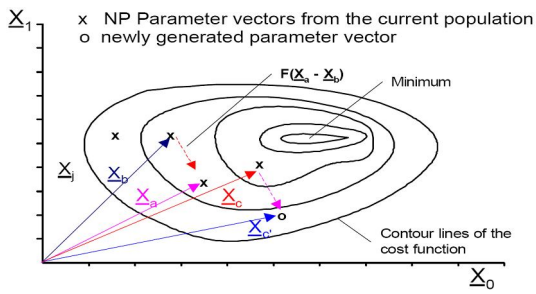

Fig. 3: Generation of mutated *Vi* in DE algorithm [17]

In order to form the trial vectors U_i, the crossover operator is applied to the mutated vector V_i and the initial population vector X_i:

$$X_i = (X_{i1}, X_{i2}, X_{i3}, X_{i4}, X_{i5}) \quad (3)$$

$$V_i = (V_{i1}, V_{i2}, V_{i3}, V_{i4}, V_{i5}) \quad (4)$$

$$U_i = (U_{i1}, U_{i2}, U_{i3}, U_{i4}, U_{i5}) \quad (5)$$

For each component of this vector, a random number in U [0, 1] selected and called $rand_j$.

$0 \le CR < 1$ is a crossover rate and $randj \le CX$, $U_{ij} = V_{ij}$ else $U_{ij} = X_{ij}$

To ensure at least some crossover exists, one component of U_i is selected randomly for V_i.

For example:

$$U_i = (V_{i1}, X_{i2}, X_{i3}, X_{i4}, V_{i5}) \quad (6)$$

First, array (V_{i1}) was selected randomly (as one definite crossover)

$rand_5 \le CR$, (V_{i5} is a definite crossover, too)

In the selection step, if the objective value (U_i) is lower than (X_i), then U_i replaces X_i in the next generation. Otherwise, Xi is kept.

IV. Combinations in DELSA (Memetic DE Algorithm)

Memetic algorithms (MAs) are one of the general heuristic search methods, while evolutionary algorithms are special solver algorithms. Evolutionary algorithms can be used as local search heuristic techniques, approximation and estimation algorithms, or some times as exact methods. "Combination" can improve the convergence speed of the best solutions, but "evolution" is too slow, and sometimes it cannot reach the solution. It has been proven MAs are very effective and successful in various problems, such as combinational optimisation [18], optimisation of non-stationary functions, and multi-objective optimisation [19]. In 1989, Dr. Moscato [20] created the Memetic algorithm for a variety of techniques based on evolutionary search combined with one or several local searches. The advantages of one algorithm can be further improved by combination with evolutionary algorithms and local search or other solution improvement methods. However, a trade off must be made between the advantages and the complexity. Therefore, how the combination is performed must be considered carefully. Any dark-coloured and bold point in Fig. 4 is a good opportunity for combination. For example, the initial population can be generated by solving a heuristic complex problem or using EA to obtain better searching capability mutation operators, showing that special limitations can be improved. However, local search can be applied to each inter-level solution or all of them.

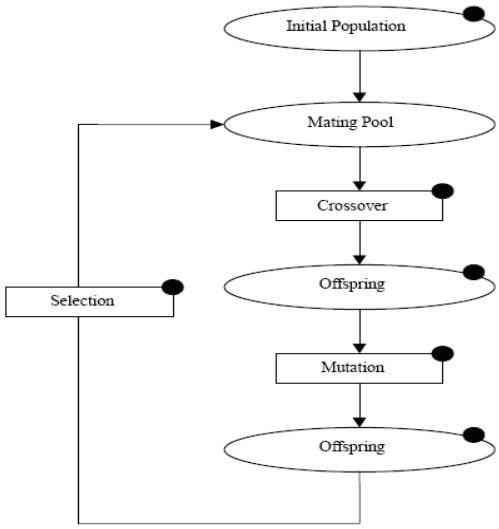

Fig. 4: Combination of EAs and LS flowchart and resulting in Memetic

Evidence shows that a problem with more special and exact information can be better solved if using the DE algorithm. The famous combination form is applying one or several local search models based on stochastic parameters applied to each member in any generation, according to Fig. 4. In order to improve the effectiveness of the algorithm, elitism can also be used, where the best offspring of a generation are transferred to the next generation (without any modification). To compare the DE algorithm performance with DELSA, the fitness evaluation should be the same for the two algorithms. Local search can also be applied to all or some offspring that have better fitness. (In this paper, Local Search is applied to all of offspring.) In this method the "combination" step is performed after the "selection" step and comparison between offspring vector and parent (from the point of view of fitness).

V. Local Search Algorithm (LS) and obtaining DELSA (Memetic DE Algorithm)

With modification of the evolution algorithm, the Memetic algorithm will change accordingly. For example, by replacing the DE algorithm with the PSO algorithm Memetic PSO algorithm will obtain, and by replacing the DE algorithm with GA and offspring with chromosomes Memetic GA will obtain. In this paper, the DE algorithm combined with local search is used. Also, the DELSA algorithm performs a search in a wide-area that may almost certainly include optimum points. As a result, complex and difficult problems can be broken down into smaller problems, which can be solved simply. The DE algorithm is an evolutionary algorithm and can be used before or after each step for the duration of the solution. In order to best adjust the solution or improve the solution, a local search can be performed after the evolutionary algorithm. Here, a performance called DELSA is introduced. To improve the robustness of the solution, an evolutionary algorithm can be performed after some period of local search. Local search can combine the objective domain with evolutionary algorithms. If evolutionary algorithms have sufficient information, they can perform successfully in the real-time domain. The special information can be transformed into mutation performance or crossover performance. This information can also be employed as the starting point of search in local search methods. In a number of cases, there are correct or combinational methods to solve sub-problems. Nevertheless, it should be noted that an optimiser is not suitable for all classes of problems, which is the reason behind the success of evolutionary algorithms in combinational structures.

The steps of the LS algorithm combined with the DE algorithm (DELSA) progress along these lines:

a) All steps of EAs, for example, the DE Algorithm up to the first step of the combination with LS.
b) Start the combination by organising offspring vectors (according to their fitness).
c) Set the best fitted offspring vectors as the population of new parents (the next generation).
d) Add a division of the stochastic initial population to the new parents population in order to achieve local search.
e) Continue the steps of EA perform local search and calculate the fitness for parent vectors, for example, the steps of the DE algorithm to produce DELSA.
f) Computation of mainly fitted offspring vectors for the next regeneration.

VI. Simulation results

In this paper, the proposed power system is a three-area power system that it was simulated in MATLAB program. The single diagram of three-area power system is shown in Fig. 5.

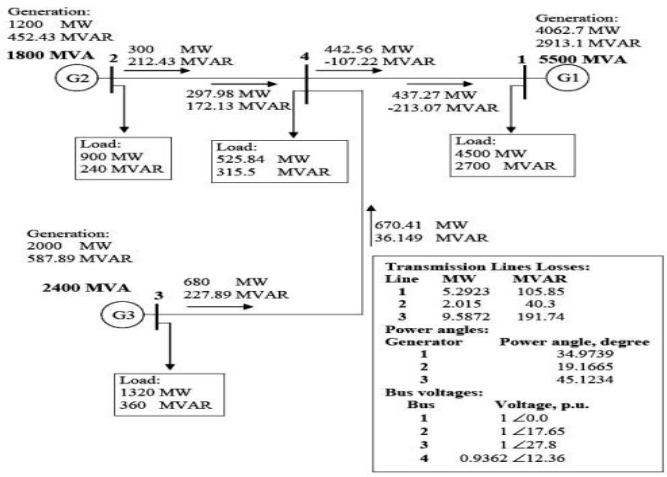

Fig. 5: Single -line diagram of three-area study system

The objective of design is to achieve optimum coordinated parameters of the PSS with the aim of recognising power system stability against local and inter-area oscillations as well as developing the damping speed of the system. The DE algorithm is utilised for this purpose. The number of solution vectors (NP) in support of the best convergence varies. To determine the justified number of vectors specifying the optimum results for local search, the severed first results have been selected compared with the best efficiency. The three-area power system is simulated by MATLAB and Simulink (non-linearity and dynamic in time-domain). Designable parameters of PSS are T_1, T_2, T_3, T_4, T_w and K_{ps}. The system considered here has some initial oscillations. Within one second after the zero time, the system contains a three-phase short-circuit fault with a resistance of 0.001 ohms for 12 cycles (12/60 seconds) at the middle of the tie line in the largest machine and middle bus (bus 4) for the worst state. The Figs show that the power system reaches instability (in a short time) after the occurrence of the fault at $t = 1$sec. The system is susceptible to instability because of the initial perturbations and conditions and becomes totally unstable after the occurrence of the three-phase short circuit fault. To achieve the preferred solution, iteration algorithm is used. Nonetheless, with all of the variation and iterations, there is a small variation in PSS parameters. Even this small variation leads to damping time reduction from an amount smaller than 7 sec to less than 6 sec and finally less than 5 sec. Objective functions used in this problem are the squared summation integral of speed variations, the difference of variation in mechanical and electrical power, and the infinity norm of speed variations of large scale machines in three areas, and the best convergence and infinity norm of speed variations are preferred. Minimum and maximum values of PSSs parameters are necessary to generate the initial population. These values are achieved by trial and error and selected by minimum convergence in minimization of the objective function (See Table I).

TABLE I
Hi & Lo values of PSS parameters to produce initial population.

PSS	Kps	Tw	T1	T2	T3	T4
Hi	35	13	0.1	0.05	5	8
Lo	20	10	0.02	0.005	1	2

Fig. 6 and 7 are shown convergence characteristics of the averaged optimum value of the objective function.

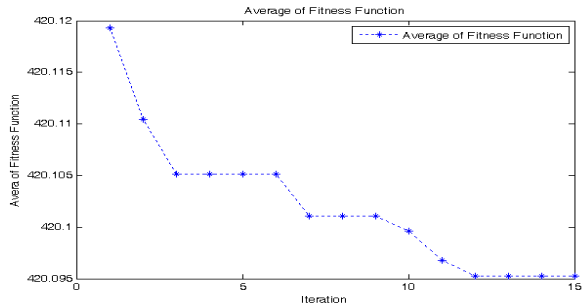

Fig. 6: Convergence characteristics of the averaged optimum value of the objective function for 15 iterations of DE.

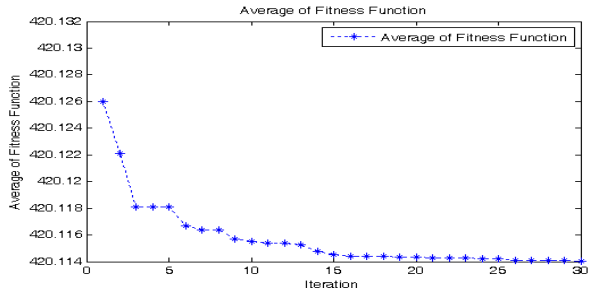

Fig. 7: Convergence characteristics of the averaged optimum value of the objective function for 30 iterations of DELSA

The difference between the damping of speed variations of different machines, in contrast with the area 1 (the largest generator) arrive at the zero in less than 5 seconds. The PSS optimum parameters after 30 iterations of the DE algorithm are easily reached in Table II.

TABLE II
Optimal values and coordinated PSS parameters obtained by DE.

PSS	*Kps*	*Tw*	*T1*	*T2*	*T3*	*T4*
Bus11	34.981	12.989	0.099	0.049	4.999	7.995
Bus12	34.998	12.992	0.099	0.050	4.992	5.320
Bus21	34.998	12.997	0.100	0.050	4.976	7.997
Bus22	34.989	12.996	0.099	0.049	4.975	7.976
Bus31	34.971	12.998	0.100	0.049	4.981	7.980
Bus32	**34.998**	**12.991**	**0.099**	**0.049**	**4.963**	**7.998**

In DELSA algorithm, to achieve the preferred solution, iteration algorithm is used. In PSS parameters just a small variation is seen, and this small value causes a reduction in the damping time from 6 sec to less than 5 sec and a drop in the overshoot in speed variation, transmitted power, output signal of PSSs and voltage. In this problem, to evaluate these results with the previous ones, the infinity norm of machine speed variations was selected as the objective function. The minimization and maximization values of the PSSs parameters for generating the initial population are shown in Table III. In Figs. 8 and 9 Convergence characteristics of the averaged optimum value of the objective function for 10 iterations of DELSA and Convergence characteristics of the averaged optimum value of the objective function for 15 iterations of DELSA are shown. Table III shows the optimal parameters of PSS after 15 iterations of DELSA.

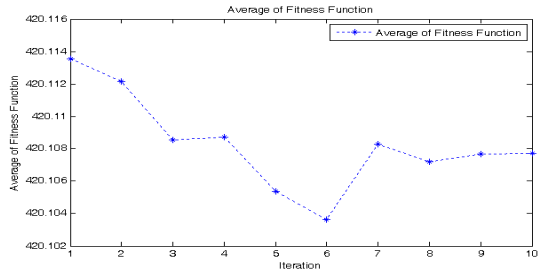

Fig. 8: Convergence characteristics of the averaged optimum value of the objective function for 10 iterations of DELSA

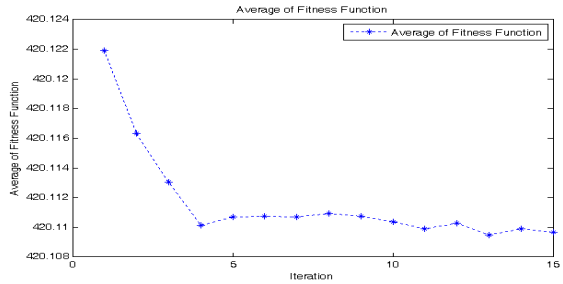

Fig. 9: Convergence characteristics of the averaged optimum value of the objective function for 15 iterations of DELSA

TABLE III
Optimal values and coordinated PSS parameters obtained by DELSA.

PSS	*Kps*	*Tw*	*T1*	*T2*	*T3*	*T4*
Bus11	38.151	14.194	0.101	0.053	5.270	8.756
Bus12	37.860	14.177	0.108	0.050	5.475	8.787
Bus21	37.971	14.206	0.102	0.053	5.196	8.352
Bus22	37.499	13.994	0.105	0.054	5.259	8.393
Bus31	37.666	14.002	0.106	0.054	5.128	8.332
Bus32	37.523	14.003	0.102	0.052	5.467	8.40

In Figs. 10-19, the variation of the speeds of the machines, the variation of tie line power between buses, the variations of PSS output signals and rotor angle difference for machine 1 are shown respectively. According to these Figs, it can be seen that stability is gated in less than 5 sec by use of the DE and DELSA algorithm. Results show that the low frequency oscillations and then local and inter-area oscillations are damped, and after damping, local modes are shifted to the left-half of the imaginary axis, and dynamic stability is obtained. Hence, according to the curves, the inter-area oscillations are damped, and therefore inter-area modes are shifted to the left-half imaginary axis plane. It can be seen that dynamic stability is attained.

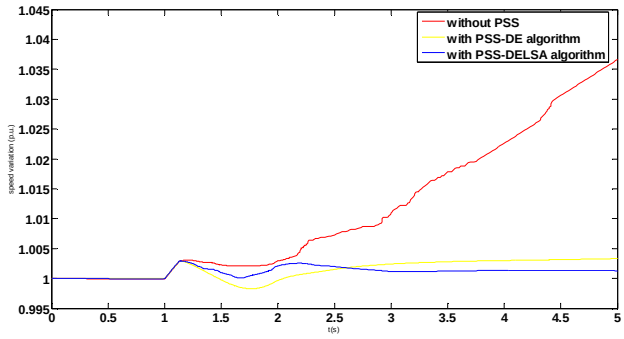

Fig. 10: Variation speed of machine1 without and with PSS by DE and DELSA algorithm

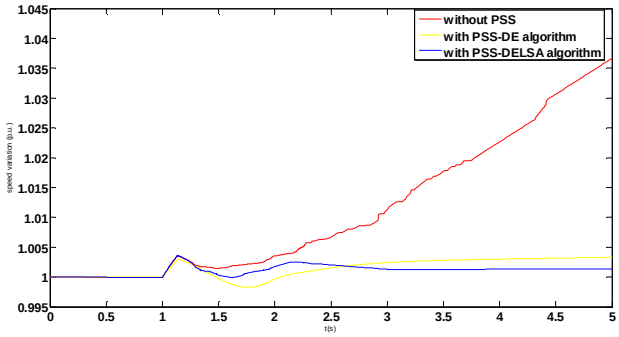

Fig. 11: Variation speed of machine 2 without and with PSS by DE and DELSA algorithm

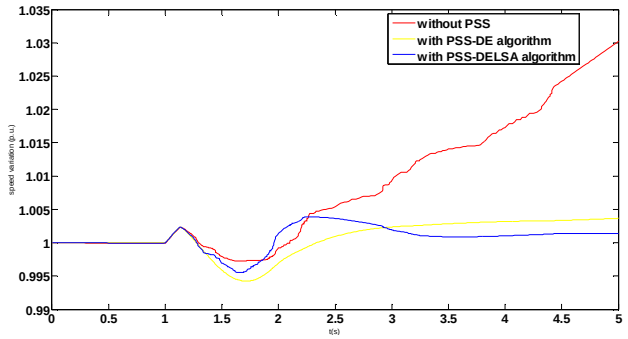

Fig. 12: Variation speed of machine 3 without and with PSS by DE and DELSA algorithm

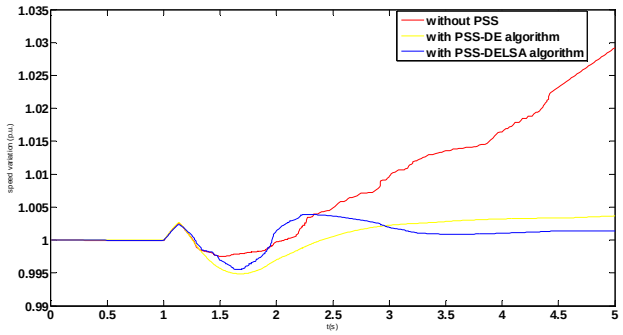

Fig. 13: Variation speed of machine 4 without and with PSS by DE and DELSA algorithm

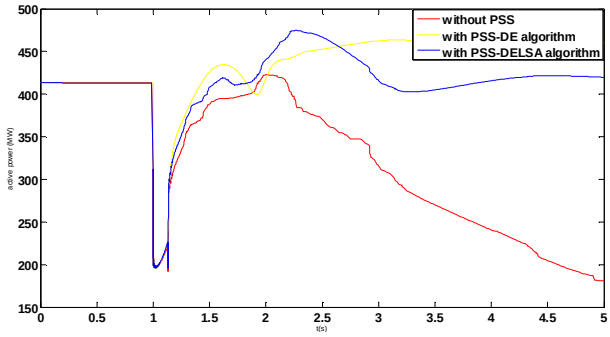

Fig. 14: Variation of tie line power between bus 1 and 2 without and with PSS by DE and DELSA algorithm

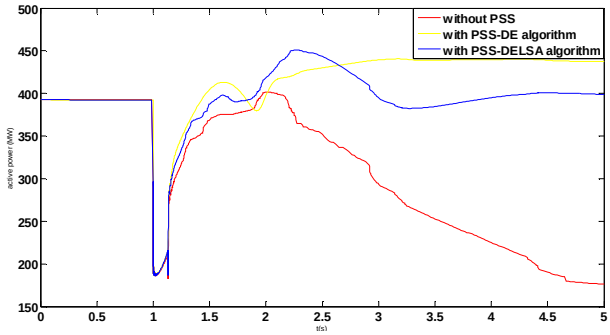

Fig. 15: Variation of tie line power between bus 2 and 3 without and with PSS by DE and DELSA algorithm

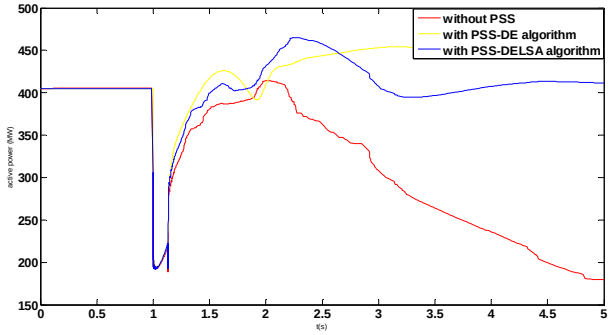

Fig. 16: Variation of tie line power between bus 3 and 1 without and with PSS by DE and DELSA algorithm

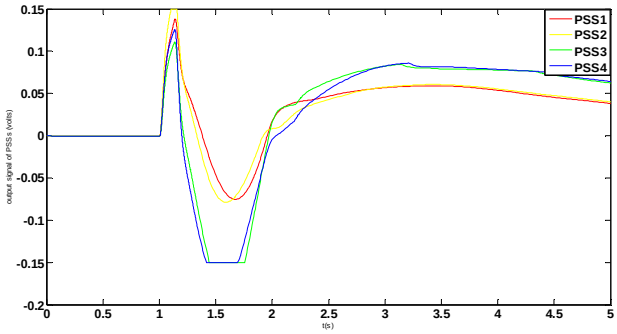

Fig. 17: Variations of PSS output signals by DE algorithm

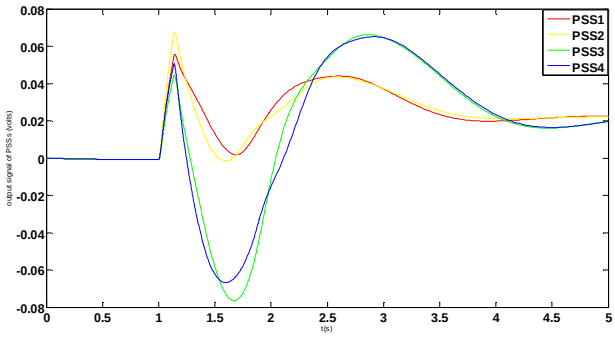

Fig. 18: Variations of PSS output signals by DELSA algorithm

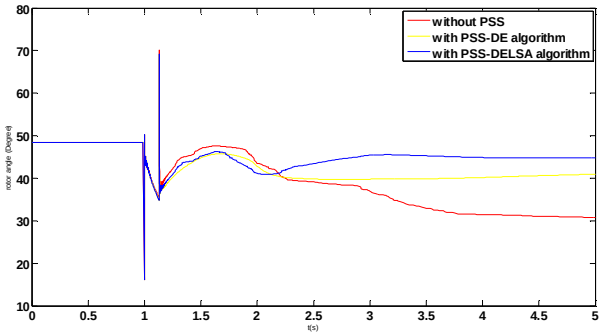

Fig. 19: Rotor angle difference for machine 1 with and without PSS by DE and DELSA algorithm

VII. Conclusion

Many investigations have been devoted to classic controller design. These methods include evolutionary algorithms, the annealing algorithm, and the stochastic evolutionary algorithm. DE is an evolutionary algorithm that

can search the correct and optimal solution space without any disagreement. The DE algorithm often attains a correct and better solution than other methods. Among these methods, the DE algorithm with a variable SCALA factor has had suitable results and converged to the optimal value. In this paper, optimal and coordinated adjustment of PSS parameters for the DE algorithm and also a combination of the DE algorithm with LS (DELSA, Memetic DE Algorithm) can damp the local and inter-area oscillations of power systems with a small number of iterations and as fast as or even faster than comparable algorithms with a larger stability margin. Comparing the results of this paper with [21] and [22], results show that the results are in agreement, and oscillations are dampened with little iteration and faster. The comparison of the DE algorithm and DELSA outcomes shows the advantages of DELSA over DE; specifically:

a) Better optimal results with a smaller amplitude in speed variation, voltage output signal of PSSs, bus voltages and inter-area transmitted power variation and a smaller number of iterations, and

b) Faster search optimal results.

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