A Firefly Algorithm Based Coordinated Design of Power System Stabilizer and Static Synchronous Series Compensator in Multi-Machine Power System

A. Kathiravan, Alamelu Nachiappan, K. Magueswary

Abstract—It is widely accepted that power system stability is an important aspect in planning and promoting electric power system. This paper presents the transient stability analysis of the three-machine nine-bus test system using MATLAB. Generator angular frequency is a reliable indicator of the stability of the power system. Change in load, power generation or fault causes a fluctuation of the speed of the generators in the power system, resulting in fluctuation of the angular frequency of the power system. So rate of change of angular frequency is used as indicator of the transient stability of the system and measures taken to maintain stability and frequency of the system. This paper presents a coordinated control tuning of power system stabilizer (PSS) with Static Synchronous Series Compensator (SSSC) by firefly algorithm to enhance the power transient stability.

Index Terms—Firefly Algorithm, Power system stabilizers, Static Synchronous Series Compensator (SSSC)

I. INTRODUCTION

Power oscillations damping in power system is one of the major challenges for the electrical utilities. Stability of these oscillations depends on the strength of the transmission system as seen by the power plant, generator excitation control systems and plant output [1]. In order to increase system stability and damp these power system oscillations, one of the formal, economical and effective solutions is to install the power system stabilizer (PSS) [2, 3] in the generator excitation system. However, the use of PSSs only may not be, in some cases, effective in providing sufficient damping for inter area oscillations, specifically for long distance power transmission.

The concept of flexible AC transmission systems (FACTS) has been feasible due to the application of high power electronic devices for power flow, voltage control, and additionally enhancing the damping of inter- area oscillations [4]. With the practical applications of the converter based FACTS controllers such as STATCOM, SSSC, and UPFC in power systems, the stability of the system can be improved.

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Among the FACTS controllers, series compensation devices like Static Synchronous Series Compensator (SSSC) are robust devices in view of power system dynamic stability point. SSSC can performs various roles in stability studies, such as scheduling power flow, reducing net power loss, providing voltage support, mitigating sub-synchronous resonance, damping the power oscillations and enhance over all stability of the system.

Introduction of PSO to search for optimal settings of rule based PSS have been discussed in [5]. Multi-objective design of multi-machine power system stabilizers using particle swarm optimization (PSO) is proposed in [6]. Power system stability enhancement via excitation and FACTS-based stabilizers is thoroughly investigated in [7]. Here, eigenvaluebased objective function to increase the system damping and improve the system response is developed and it is optimized using real-coded genetic algorithm. However, from an evolutionary point of view, the performance of the PSO is better than that of GA [8] and the authors claimed that PSO arrives at its final parameter values in fewer generations than the GA. Moreover the authors tested several stabilizers like PSS, SVC, TCSC and TCPS individually to enhance system stability.

In literature several researchers proposes the coordination of PSS with FACTS controllers to enhance dynamic performance of the power system. In [9], the authors discussed global tuning procedure for PSS and FACTS devices using a parameter-constrained nonlinear optimization algorithm. A robust coordinated design of a PSS and FACTS based stabilizer is thoroughly investigated in [10], here an eigenvalue-based objective function is optimized using GA. In [11] the authors develop a novel algorithm for simultaneous coordinated designing of PSS and FACTS based controllers using bacterial swarm optimization. A SSSC damping controller is designed to improve power system oscillation stability [12].

SSSC uses a voltage source converter to inject a controllable voltage in quadrature with the line current of a power network belongs to the family of series FACTS devices. Such a device is rapidly able to provide both capacitive and inductive impedance compensation independent of the line current. Moreover, SSSC with a properly designed external damping controller can also be used to damp the low frequency power oscillations in power systems [13].

The firefly algorithm (FA) is a meta-heuristic, nature-inspired, optimization algorithm which is based on the social (flashing) behavior of fireflies, or lighting bugs, in the summer sky in the tropical temperature regions [14]. It was developed by Dr. Xin-She Yang at Cambridge University in 2007, and it is based on the swarm behavior such as fish, insects, or bird schooling in nature. In particular, although the firefly algorithm has many similarities with other algorithms which are based on the so-called swarm intelligence, such as the famous Particle Swarm Optimization (PSO), Artificial Bee Colony optimization (ABC), and Bacterial Foraging (BFA) algorithms, it is indeed much simpler both in concept and implementation.

Hence, the present work deals with simultaneous coordinated tuning of PSS and SSSC for multi-machine power system using firefly algorithm. The PSS coordinated with SSSC improves the transient stability. Hence, the combination of these controllers can enhance the overall stability of power system. The proposed controllers are tested individually as well as simultaneously with time-domain simulations. The robustness of the proposed controller to enhance the power system dynamic performance is tested under different loading conditions.

II. POWER SYSTEM DYNAMICAL MODEL

A. Synchronous Machine Modelling

In this study, the three-machine nine-bus power system [3] shown in Fig. 1 is considered. The generators are modeled in third order model [2], which consists of electro-mechanical swing equation, and q-axis generator internal voltage equation. The dynamic equations are shown equations (1)-(3).

$$\dot{\delta}_i = \omega_i - \omega_0 \tag{1}$$

$$\dot{\omega}_i = \frac{D_i}{M_i}[\omega_i - \omega_0] + \frac{\omega_0}{M_i}[P_{mi} - P_{ei}] \tag{2}$$

$$\dot{E}'_{qi} = \frac{1}{T'_{d0i}}[E_{fdi} - (X_{di} - X'_{di})I_{di} - E'_{qi}] \tag{3}$$

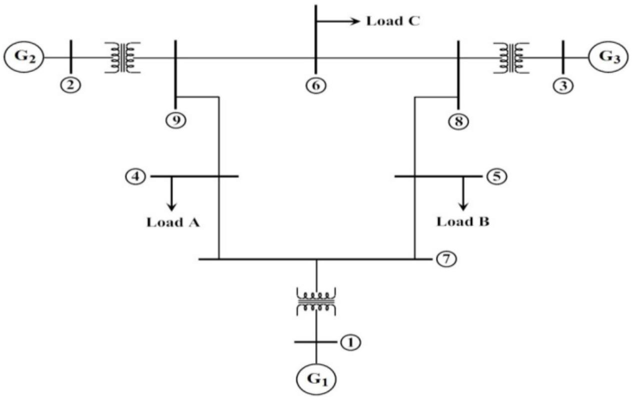

Fig. 1. Three-machine nine-bus system

B. Exciter System Modelling

The conventional excitation system shown in Fig. 2 is considered. It represents an automatic voltage regulator (AVR) and a power system stabilizer (PSS). The PSS transfer function consisting of PSS gain, wash-out and two stage leadlag compensator. The wash-out acts as high pass filter, whereas the lead-lag compensator provides phase lead to compensate the phase lag between excitation and the generator electrical torque. The dynamic equation is given [2] by:

$$\dot{E}_{fd} = \frac{1}{T_A}[K_A[V_{ref} - V_t + U_{pss}] - E_{fd}] \tag{4}$$

where Vref is the reference terminal voltage of the generator, KA and TA are the gain and time constant of the AVR. UPSS is the output of conventional lead-lag based PSS.

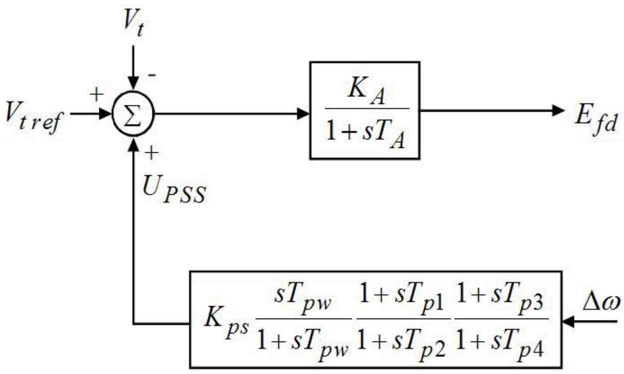

Fig. 2. Conventional excitation system with a PSS

C. Static Synchronous Series Compensator

The SSSC installed on the transmission line is shown in Fig. 3. The SSSC consists of a three-phase voltage source converter (VINV), a boosting series coupling transformer with a leakage reactance of XSCT and a DC capacitor (CDC). The two input control signals to the SSSC are m and . Where signal is the phase of the injected voltage and is kept in quadrature with the line current (loss of the inverter is ignored), and signal m is the amplitude modulation ratio of the Pulse Width Modulation (PWM) based VSC, that determines the magnitude of the inserted voltage [13,15].

The dynamic model of SSSC to study power system stability is as follows [15]:

$$\overline{I_{ts}} = I_{tsd} + jI_{tsq} = I_{TS}\angle\phi \tag{5}$$

$$\overline{V_{INV}} = mkV_{DC}(\cos\Psi + j\sin\Psi) = mkV_{DC}\angle\Psi \tag{6}$$

$$\Psi = \phi \pm 90 \tag{7}$$

$$\frac{dV_{DC}}{dt} = \frac{I_{DC}}{C_{DC}} = \frac{mk}{C_{DC}}(I_{tsd}\cos\Psi + I_{tsq}\sin\Psi) \tag{8}$$

where k is the fixed ratio between AC and DC voltage of SSSC voltage source inverter.

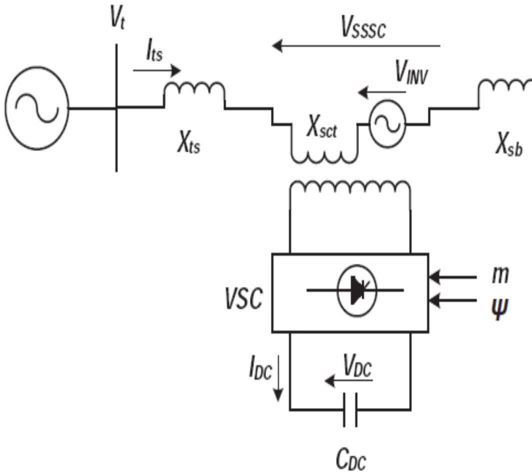

Fig. 3. Power system model with SSSC

III. THE FIREFLY ALGORITHM

A. Description

The firefly algorithm (FA) is a meta-heuristic, nature-inspired, optimization algorithm which is based on the social (flashing) behavior of fireflies, or lighting bugs, in the summer sky in the tropical temperature regions [14]. The firefly algorithm has three particular idealized rules which are based on some of the major flashing characteristics of real fireflies [15-19]. These are the following:

(1) All fireflies are unisex, and they will move towards more attractive and brighter ones regardless their sex.

(2) The degree of attractiveness of a firefly is proportional to its brightness which decreases as the distance from the other firefly increases due to the fact that the air absorbs light. If there is not a brighter or more attractive firefly than a particular one, it will then move randomly.

(3) The brightness or light intensity of a firefly is determined by the value of the objective function of a given problem. For maximization problems, the light intensity is proportional to the value of the objective function.

B. Attractiveness

In the firefly algorithm, the form of attractiveness function of a firefly is the following monotonically decreasing function [15]:

$$\beta(r) = \beta_0{}^{*}\exp\left(-\gamma r^{m}\right), \qquad m \geq 1 \tag{9}$$

C. Distance

The distance between any two fireflies i and j, at positions xi and xj , respectively, can be defined as a Cartesian or Euclidean distance as follows [15, 16]:

$$r_{ij} = \left\| x_i - x_j \right\| = \sqrt{\sum_{k=1}^{d} (x_{i,k} - x_{j,k})^2} \tag{10}$$

where xi, k is the kth component of the spatial coordinate xi of the ith firefly and d is the number of dimensions we have, for d = 2, we have

$$r_{ij} = \sqrt{\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2} \tag{11}$$

However, the calculation of distance r can also be defined using other distance metrics, based on the nature of the problem, such as Manhattan distance or Mahalanobis distance.

D. Movement

The movement of a firefly i which is attracted by a more attractive (i.e., brighter) firefly j is given by the following equation [15, 16]:

$$x_i = x_i + \beta_0 * \exp\left(-\gamma r_{ij}^{\ 2}\right) * \left(x_j - x_i\right) + a * \left(rand - \frac{1}{2}\right) \tag{12}$$

where the first term is the current position of a firefly, the second term is used for considering a firefly’s attractiveness to light intensity seen by adjacent fireflies, and the third term is used for the random movement of a firefly in case there are not any brighter ones. The coefficient α is a randomization parameter determined by the problem of interest, while rand is a random number generator uniformly distributed in the space [0,1]. As we will see in this implementation of the algorithm, we will use β0 = 1.0, α ∈ [0, 1] and the attractiveness or absorption coefficient γ = 1.0, which guarantees a quick convergence of the algorithm to the optimal solution.

E. Convergence and Asymptotic Behavior

The convergence of the algorithm is achieved for any large number of fireflies (n) if n >> m, where m is the number of local optima of an optimization problem [17]. In this case, the initial location of n fireflies is distributed uniformly in the entire search space. The convergence of the algorithm into all the local and global optima is achieved, as the iterations of the algorithm continue, by comparing the best solutions of each iteration with these optima.

However, it is under research a formal proof of the convergence of the algorithm and particularly that the algorithm will approach global optima when n → ∞ and t >> 1 [18].

In practice, the algorithm converges very quickly in less than 80 iterations and less than 50 fireflies, as it is demonstrated in several research projects using some standard test functions [19]. Indeed, the appropriate choice of the number of iterations together with the γ, β, α, and n parameters highly depends on the nature of the given optimization problem as this affects the convergence of the algorithm and the efficient find of both local and global optima. Note that the firefly algorithm has computational complexity of O (n2), where n is the population of fireflies. The larger population size becomes the greater the computational time is [16-19]. The flowchart of the firefly algorithm is illustrated in Fig. 4.

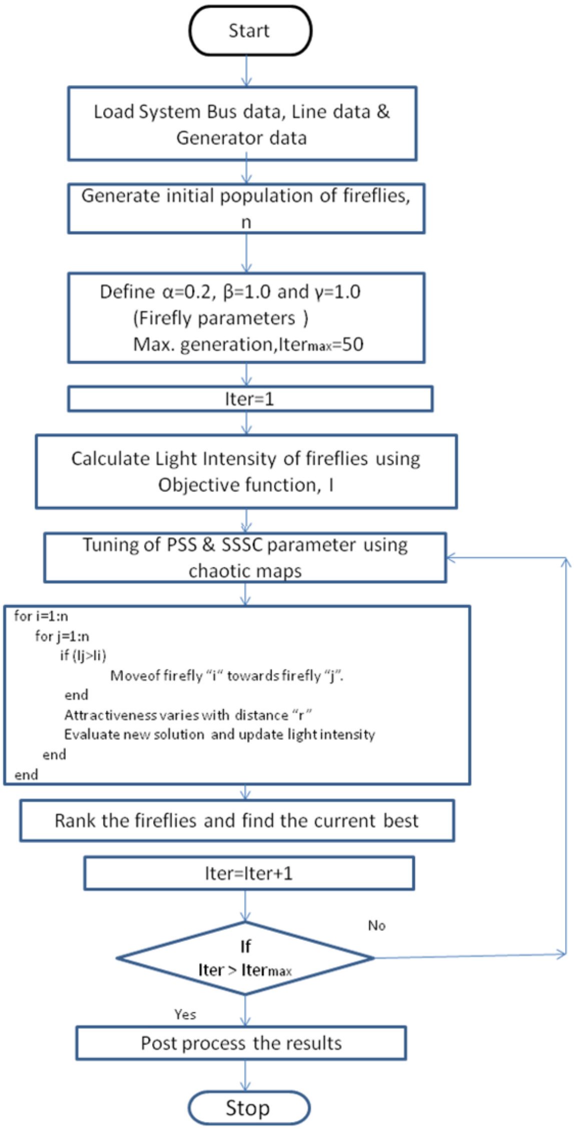

Fig. 4. Flowchart of firefly algorithm

IV. OBJECTIVE FUNCTION AND IMPLEMENTATION

Objective function is a mathematical expression describing a relationship of the optimization parameters that uses the optimization parameters as inputs. In this paper, for optimization of coordinated damping controller parameters, integral of time-multiplied absolute value of error (ITAE) is considered as objective function. Since integral squired error (ISE) is considered only error and there is no importance is given to time. But for power system stability problems, it is required that settling time should be less and also oscillations should die out soon. However, the main objective is to damp the power oscillations and maintain the overall stability of the system. This can be achieved by minimizing the value of speed deviations of generators. So the objective function is formulated with the integration of speed variation. The objective function is given by

$$J = \int_0^t t[|\omega 2 - \omega 1| + |\omega 3 - \omega 1|]dt \tag{13}$$

where t is total simulation time, ω1, ω2, and ω3 are speeds of generators G1, G2, and G3 respectively.

In this study, the coordinated controller parameters of PSS as well as SSSC are optimized based on the objective function given in Eq. (13) using firefly algorithm.

V. SIMULATION RESULTS AND DISCUSSION

In this analysis the three-machine nine-bus system is considered. The PSSs installed at generators G2, G3 and a simple exciter installed at generator G1. The performance of the test system is analyzed under different loading conditions given in table 1.1. The non-linear time domain simulation is carried out using MATLAB programming for a three phase fault.

Now, let us assume that a three phase to ground fault takes place at bus 7 at t = 0.5 sec. To simulate this fault, the element Y77 is increased 1000 times to represent very high admittance to ground. The fault is assumed to be cleared at t = 0.6 sec. To simulate this event (clearing of fault), the value of Y77 is restored to its pre-fault value at t = 0.6 sec.

Table 1.1 Test system different loading conditions

	Nominal Loading		Heavy Loading		Lightly Loading	
	P	**Q**	**P**	**Q**	**P**	**Q**
			Generator			
G1	71.64	27.05	134.91	43.31	9.11	17.64
G2	163.00	6.65	163.00	17.87	163.00	-2.83
G3	85.00	-10.86	85.00	-0.91	85.00	-19.17
			Load			
L1	0	0	0	0	0	0
L2	0	0	0	0	0	0
L3	0	0	0	0	0	0
L4	0	0	0	0	0	0
L5	125	50	150	60	100	40
L6	90	30	108	36	72	24
L7	0	0	0	0	0	0
L8	100	35	120	42	80	28
L9	0	0	0	0	0	0

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A. Nominal Loading Condition

The effectiveness of proposed integrated controller is tested with the test system under nominal loading. The fig. 5.1(a), (b) & (c) represents the rotor angle changes of Generator 1, 2 and 3 with respect to synchronous angular speed.

The oscillations are not damped in case of system without controller due to the large disturbance. Whereas the integrated controller shows better damping effect to power oscillations when compare with individual controllers. The settling time of these oscillations are also very good for the system having integrated controller. Power flow results after installing SSSC is given in the table 1.2.

Injected SSSC Series Voltage at line 3 : Vse (pu) = 0.0363 @ 0.0405

Table 1.2 Power flow after SSSC installed - Normal load

Bus	V	Angle	Injection		Generation		Load	
No	pu	Degree	MW	MVar	MW	Mvar	MW	MVar
1.00	1.04	0.00	71.59	27.05	71.59	27.05	0.00	0.00
2.00	1.03	9.28	163.00	6.66	163.00	6.66	0.00	0.00
3.00	1.03	4.67	85.00	-10.86	85.00	-10.86	0.00	0.00
4.00	1.03	-2.22	0.00	0.00	0.00	0.00	0.00	0.00
5.00	1.00	-3.99	-125.00	-50.00	0.00	0.00	125.00	50.00
6.00	1.01	-3.68	-90.00	-30.00	0.00	0.00	90.00	30.00
7.00	1.03	3.72	0.00	0.00	0.00	0.00	0.00	0.00
8.00	1.02	0.73	-100.00	-35.00	0.00	0.00	100.00	35.00
9.00	1.03	1.97	0.06	0.00	0.06	0.00	0.00	0.00
Total			4.64	-92.16	319.64	22.85	315.00	115.00

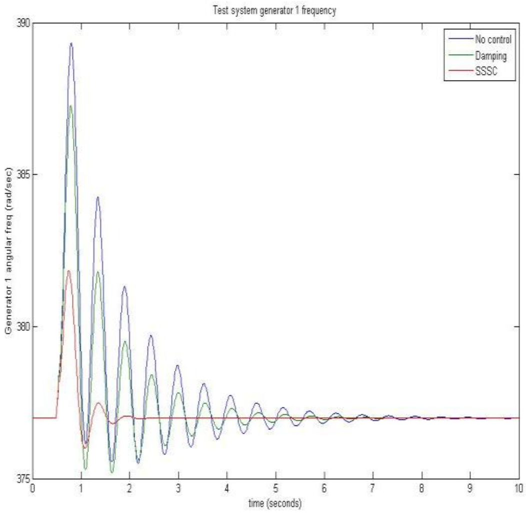

Fig. 5.1(a) Generator 1 frequency

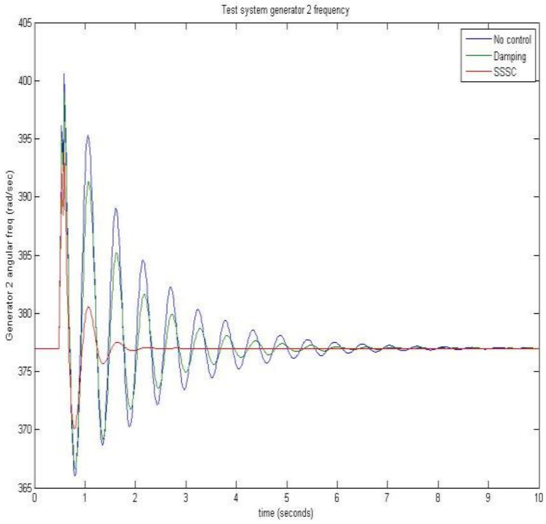

Fig. 5.1(b) Generator 2 frequency

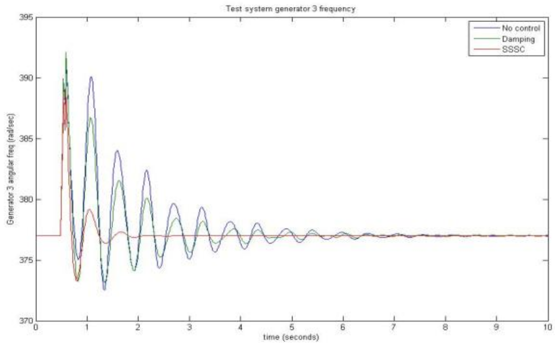

Fig. 5.1(c) Generator 3 frequency

B. Heavy Loading Condition

The effectiveness of proposed integrated controller is tested with the test system under heavy loading. The fig. 5.2(a), (b) & (c) represents the rotor angle changes of Generator 1, 2 and 3 with respect to synchronous angular speed. The oscillations are not damped in case of system without controller due to the large disturbance. Whereas the integrated controller shows better damping effect to power oscillations when compare with individual controllers. The settling time of these oscillations are also very good for the system having integrated controller. Power flow results after installing SSSC is given in the table 1.3.

Injected SSSC Series Voltage at line 4 : Vse (pu) = 0.0354 @ 3.6329

Table 1.3 Power flow after SSSC installed - Heavy load

Bus	V	Angle	Injection		Generation		Load	
No	pu	Degree	MW	MVar	MW	Mvar	MW	MVar
1	1.04	0	134.814	43.293	134.814	43.293	0	0
2	1.025	4.7499	163	17.869	163	17.869	0	0
3	1.025	0.2409	85	-0.917	85	-0.917	0	0

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4	1.0188	-4.203	0	0	0	0	0	0
5	0.9808	-7.686	-150	-60	0	0	150	60
6	1.0002	-7.140	-107.90	-36	0.096	0	108	36
7	1.019	-0.847	0	0	0	0	0	0
8	1.005	-4.273	-120	-42	0	0	120	42
9	1.0267	-2.472	0	0	0	0	0	0
Total			4.91	-77.75	382.91	60.245	378	138

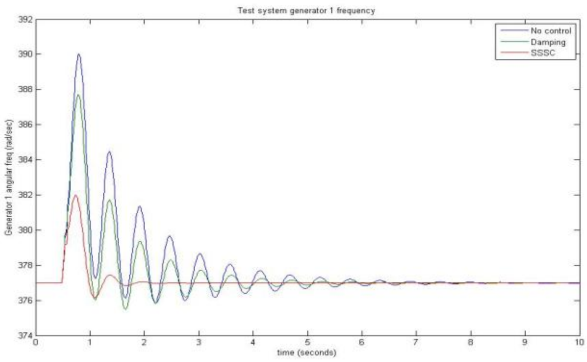

Fig. 5.2(a) Generator 1 frequency

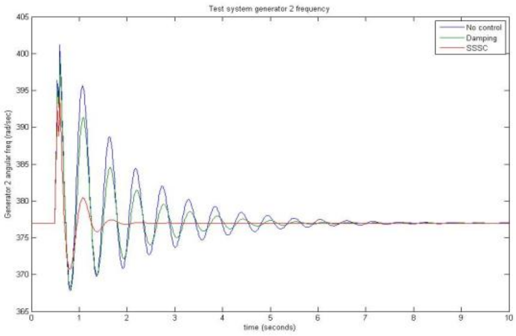

Fig. 5.2(b) Generator 2 frequency

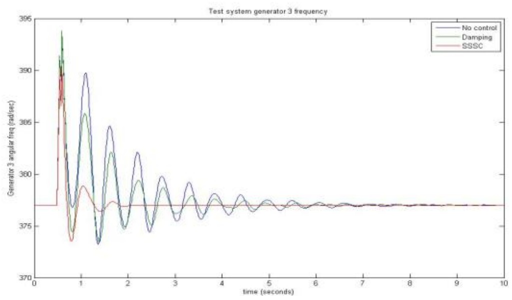

Fig. 5.2(c) Generator 3 frequency

C. Light Loading Condition

The effectiveness of proposed integrated controller is tested with the test system under light loading. The fig. 5.3(a), (b) & (c) represents the rotor angle changes of Generator 1, 2 and 3 with respect to synchronous angular speed. The oscillations are not damped in case of system without controller due to the large disturbance. Whereas the integrated controller shows better damping effect to power oscillations when compare with individual controllers. The settling time of these oscillations are also very good for the system having integrated controller. Power flow results after installing SSSC is given in the table 1.4.

Injected SSSC Series Voltage at line 4: Vse (pu) = 0.1896 @ 6.1904

Table 1.4 Power flow after SSSC installed - Light load

Bus	V	Angle	Injection		Generation		Load	
No	pu	Degree	MW	MVar	MW	Mvar	MW	MVar
1	1.04	0	8.768	17.651	8.768	17.651	0	0
2	1.025	13.6753	163	-2.829	163	-2.829	0	0
3	1.025	8.9562	85	-19.18	85	-19.18	0	0
4	1.0302	-0.2701	0	0	0	0	0	0
5	1.0074	-0.411	-100	-40	0	0	100	40
6	1.0224	-0.3237	-71.65	-24	0.344	0	72	24
7	1.0315	8.1461	0	0	0	0	0	0
8	1.0256	5.5706	-80	-28	0	0	80	28
9	1.0371	6.2705	0	0	0	0	0	0
Total			5.112	-96.36	257.112	-4.362	252	92

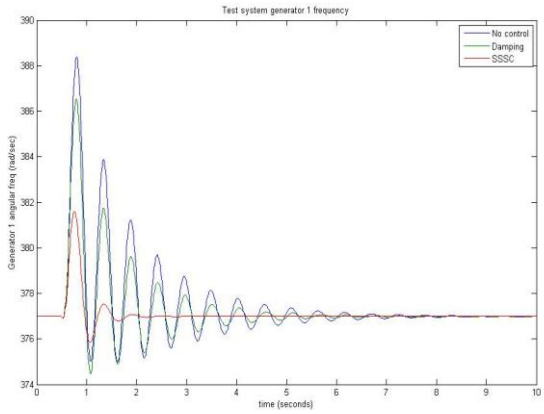

Fig. 5.3(a) Generator 1 frequency

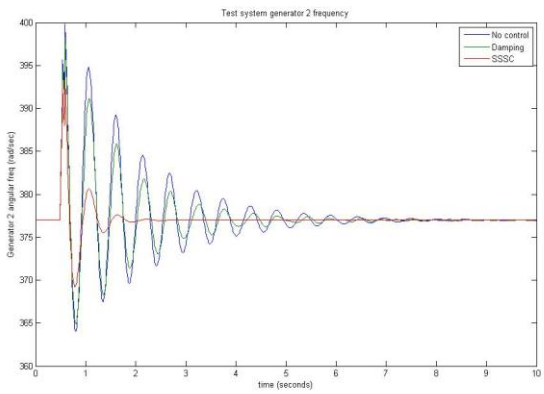

Fig. 5.3(b) Generator 2 frequency

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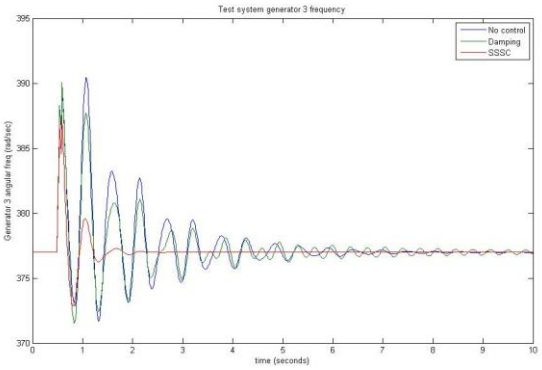

Fig. 5.3(c) Generator 3 frequency

VI. CONCLUSIONS

In this paper, optimized coordinated control of a power system stabilizer (PSS) with SSSC is discussed. An objective function is minimized using firefly algorithm for finding the optimal control parameters of SSSC and PSS. The time domain simulation of a non-linear system is carried out in MATLAB software package. The robustness of the proposed coordinated controller is investigated by testing its performance under normal, heavy and light loading conditions. The simulation results show that the test system dynamic performance and overall damping effect are enhanced by simultaneous tuning of PSS and SSSC. Therefore, coordinated tuning and control of PSS and SSSC based damping controller provides better damping of power oscillations.

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