PSS with Multiple FACTS Controllers Coordinated Design and Real-Time Implementation Using Advanced Adaptive PSO

Rajendraprasad Narne, P. C. Panda

***Abstract*—**In this article, coordinated tuning of power system stabilizer (PSS) with static var compensator (SVC) and thyristor controlled series capacitor (TCSC) in multi-machine power system is proposed. The design of proposed coordinated damping controller is formulated as an optimization problem and the controller gains are optimized instantaneously using advanced adaptive particle swarm optimization (AAPSO). The objective function is framed with the inter-area speed deviations of the generators and it is minimized using AAPSO to improve the dynamic stability of power system under severe disturbance. The proposed coordinated controller performance is evaluated under a wide range of system operating conditions with three-phase fault disturbance. Using time domain simulations the damping characteristics of proposed controller is compared with individually tuned PSS, SVC and TCSC controllers. Finally, the real-time simulations are carried out in Opal-RT hardware simulator to synchronize the proposed controller performance in the real world.

***Keywords*—**Advanced adaptive particle swarm optimization, Coordinated design, Power system stabilizer, Real-time implementation, static var compensator, Thyristor controlled series capacitor.

I. Introduction

THE continuous growth in electric power demand causes complex interconnections among power utilities to transfer more power. The building of new trans-mission lines and expansion of existing transmission systems are becoming more and more difficult due to economic and regulatory policies. All together, the power systems are almost operated ever closer to their transient and dynamic stability limits. In such scenario the power system has high chance to lose its stability even for small disturbances. In order to enhance system stability, one of the conventional, economical and effective solutions is to install the power system stabilizer (PSS) [1], [2]. 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 [3]. Among the FACTS controllers, series compensation devices like thyristor controlled series capacitor (TCSC) are robust devices in view of power system dynamic stability point. TCSC can perform 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. TCSC is thyristor based controller, by controlling the effective reactance, the TCSC will control the power transfer.

Particle Swarm Optimization (PSO) technique, developed by Kennedy and Eberhart [4], is found applicability and has been used extensively in solving various problems in power systems. 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, eigenvalue-based 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.

Coordination means simultaneous tuning of parameters of a number of decentralized controllers to ensure dynamic and steady state performance criteria. 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 TCSC based stabilizer is thoroughly investigated in [10]; here an eigenvalue-based objective function is optimized using GA. The authors develop a novel algorithm for simultaneous coordinated designing of PSS and TCSC based controllers using PSO in [11] and using bacterial swarm optimization in [12]. The probabilistic theory based coordinate design of SVC and PSS is discussed in [13]. Here, the conventional eigenvalue analysis is extended to probabilistic environment for robust damping controller site selection and optimization of objective functions. A novel coordinated design of PSSs and SVC via bacteria foraging optimization

Rajendraprasad Narne is with the National Institute of Technology, Rourkela, Orissa, India (e-mail: nrajnitrkl@gmail.com).
P. C. Panda, is with the National Institute of Technology, Rourkela, Orissa, India (e-mail: pcpanda@nitrkl.ac.in).

algorithm in a multi-machine is presented in [14].

The coordinated tuning of SVC and TCSC is discussed by few authors. A nonlinear design technique based on direct feedback linearizing is used to deduce the control scheme for the TCSC and SVC. The coordination between two pieces of equipment is also designed in [15]. In order to adapt to the changes of operating modes and active power, of generators, a neural network algorithm is applied in [16] to determine the control parameters of SVC and TCSC damping controller. In both the above mentioned papers the authors treated SVC as supplement of the TCSC. Finally, [17] the integral of squared error technique is used for global tuning of the stabilizers and here the authors consider multi-machine power system equipped with a TCSC and an SVC as well as three PSSs is applied to demonstrate the efficiency and robustness of the proposed tuning procedure. In addition to all these studies, the Real-time implementation and coordinated design of PSS with multiple FACTS controllers in multi-machine power system become desirable and innovative future scope for appropriate validation of the proposed design, which has been attempted in this work.

The present work deals with simultaneous coordinated tuning of PSS with SVC and TCSC in multi-machine power system. Here, the control parameters of combined coordinated controller are optimized by minimizing an objective function using AAPSO. The AAPSO based coordinated PSS with SVC and AAPSO based coordinated PSS with TCSC are presented and their performances are compared with the AAPSO based coordinated design of PSS with SVC and TCSC using time-domain simulations. The robustness of the proposed controller to enhance the power system dynamic performance is tested under different loading conditions. Finally the simulation results are presented to demonstrate the effectiveness of the proposed controller to enhance the power system dynamic stability. Apart from that, we validated the proposed controller by implementing real-time in OPAL-RT hardware simulator and the simulation results are compared with the real-time results.

II. Advanced Adaptive Particle Swam Optimization (AAPSO)

A. Conventional PSO: An Over View

Particle swarm optimization is a population based stochastic optimization technique. It was developed by James Kennedy and Russel C. Eberhart in 1995 [18]. PSO has a flexible and well balanced mechanism to enhance the global and local exploration abilities. Compare to GA, PSO is easy to implement and it consists of only few parameters to adjust. The position and velocity vectors of the i[th] particle in the D-dimensional space can be represented as $X_i = (x_{i1}, x_{i2}, \ldots\ldots\ldots\ldots, x_{id})$ and $V_i = (v_{i1}, v_{i2}, \ldots\ldots\ldots\ldots, v_{id})$ respectively. The particles in the optimization problem share their information with each other and run towards the best trajectory to find optimum solution in iterative process. In each iteration particles will update their velocities and positions by using the following equations:

$$V_{i,\,iter+1} = wV_{i,\,iter} + c_1 r_1 (P_{i,\,iter}^{best} - X_{i,\,iter}) + c_2 r_2 (G_{i,\,iter}^{best} - X_{i,\,iter}) \quad (1)$$

$$X_{i,\,iter+1} = X_{i,\,iter} + V_{i,\,iter+1} \quad (2)$$

where $V_{i,iter}$ and $X_{i,iter}$ represent the velocity vector and the position vector of i[th] particle at iteration 'iter', $P_{i,iter}^{best}$ and $G_{i,iter}^{best}$ are personal best position of i[th] particle and global best position of swarm in the iteration 'iter'. The constants c_1 and c_2 are the positive cognitive and social components that are responsible for varying the particle velocity towards the pbest and gbest, respectively, r_1 and r_2 are two random numbers in the range [0-1]. The inertia weight w is responsible for dynamically adjusting the velocity of the particles. To enhance the efficiency of PSO, one can adjust the inertia weight w to linearly reduce during the iterations. The inertia weight is updated by the following equation

$$w = (w_{\max} - w_{\min}) \times \left(\frac{iter_{\max} - iter}{iter_{\max}} \right) + w_{\min} \quad (3)$$

where $iter_{\max}$ is the maximum number of iterations and iter is the current number of iteration. $w_{\max}$ and $w_{\min}$ are maximum and minimum values of inertia weight respectively. The typical range of w from 0.9 at the beginning of the search to 0.4 at the end of the search [19].

B. Advanced Particle Swarm Optimization

The conventional PSO has a drawback of its inadequate convergence towards global optima. To guarantee the algorithm convergence and avoiding the explosion of the particle swarm (i.e. the state where the particles velocities and positional coordinates careen toward infinity) an advance PSO technique was introduced by Clerc et al. [20]. The advanced PSO hosting a new parameter called constriction factor 'K' in the velocity equation. Hence, the particles in the swarm can update their velocities and positions by using the following equations:

$$V_{i,\,iter+1} = K\,[wV_{i,\,iter} + c_1 r_1 (P_{i,\,iter}^{best} - X_{i,\,iter}) + c_2 r_2 (G_{i,\,iter}^{best} - X_{i,\,iter})] \quad (4)$$

$$X_{i,\,iter+1} = X_{i,\,iter} + V_{i,\,iter+1} \quad (5)$$

where $K = \dfrac{2}{\left| 2 - \varphi - \sqrt{\varphi^2 - 4\varphi} \right|}$, $\varphi = c_1 + c_2, \varphi > 4$

Usually c_1 and c_2 are selected in the range of 0 to 4.

C. Advanced Adaptive Particle Swarm Optimization

In population based optimization methods, the policy is to encourage the individuals to roam through the entire search space without clustering around local optima during the initial stages. However, during latter stages to find the optimum solution efficiently convergence towards the global optima should be encouraged. The concept of time-varying acceleration coefficients (TVAC) c_1 and c_2 in addition to time-varying inertia weight factor is introduced in advanced adaptive PSO technique such that AAPSO can efficiently control the local search and provide adequate convergence towards the global optimum solution. During initial stages a large c_1 and small c_2 allows the particles to move around search space instead of moving the population best prematurely. At latter stages a small c_1 and large c_2 allows the particles to converge towards the global optima. Acceleration coefficients are adaptively changed as follows [21]:

$$c_1 = c_1^{final}\left(\frac{iter}{iter_{\max}}\right) + c_1^{initial}\left(\frac{iter_{\max} - iter}{iter_{\max}}\right), \qquad c_1^{final} < c_1^{initial} \quad (6)$$

$$c_2 = c_2^{final}\left(\frac{iter}{iter_{\max}}\right) + c_2^{initial}\left(\frac{iter_{\max} - iter}{iter_{\max}}\right), \qquad c_2^{final} > c_2^{initial} \quad (7)$$

where $c_1^{initial}, c_2^{initial}$ and c_1^{final}, c_2^{final} are initial and final values of the acceleration coefficients c_1 and c_2 respectively.

III. Problem Formulation

A. Power System Model

An interconnected power system consisting of N generators can be modeled by a set of nonlinear differential equations as

$$\dot{X} = AX + BU \quad (8)$$

where X is the vector of state variables, U is the vector of input variables.

In this study, the generator is represented by a third-axis model which is clearly described in [2], and each generator has PSS installed on it. Moreover, the power system consists of a TCSC damping controller. Then the variables in the state equation can be written as:

$$X = [\delta_i \quad \omega_i \quad E'_{qi} \quad E_{fdi}] \text{ and } U = [U_{pss} \quad B_{SVC} \quad X_{TCSC}], \text{ where } i = 1, 2, ..., \text{N}.$$

Here, δ, ω, E'_q and E_{fd} are the rotor angle, rotor speed, internal voltage and field voltage respectively. Also, U_{PSS}, B_{SVC} and X_{TCSC} are the PSS, SVC and TCSC output stabilizing signals, respectively.

The single line diagram of system under study is shown in Fig. 1. The details of this 3-machine 9-bus system are given in [1]. This system is operated under wide range of loading conditions (namely light, normal and heavy) and the loading details are given in Table I.

B. Excitation System Modeling

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 lead-lag 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 [1] by:

$$\dot{E}_{fd} = \frac{1}{T_A}\left[K_A[V_{ref} - V_t + U_{PSS}] - E_{fd}\right] \quad (9)$$

where Vref is the reference terminal voltage of the generator, K_A and T_A are the gain and time constant of the AVR. U_{PSS} is the output of conventional lead-lag based PSS.

C. SVC Based Damping Controller

The design of FACTS based damping controllers are based on conventional lead-lag structure. The input signal to the controller is speed deviation of the generator. The controller block consists of a gain block, washout block and two stage lead-lag blocks. The controller structure of SVC is shown in Fig. 3. Here, the SVC modeled as a variable susceptance BSVC. The dynamic equation of SVC-based controller is given as

$$\dot{B}_{SVC} = \frac{1}{T_S}\left[K_S(B_{SVCref} - U_{SVC}) - B_{SVC}\right] \quad (10)$$

where, B_{SVCref} is the reference susceptance of SVC, K_S and T_S are the gain and time constant of the SVC. U_{SVC} is the output of conventional lead-lag SVC damping stabilizer.

D. TCSC Based Damping Controller

The TCSC damping controller can be modeled as a variable reactance for the load flow and dynamic stability studies. The controller structure of TCSC is shown in Fig. 4. The dynamic equation for reactance of TCSC is given by.

$$\dot{X}_{TCSC} = \frac{1}{T_T}\left[K_T(X_{TCSCref} - U_{TCSC}) - X_{TCSC}\right] \quad (11)$$

where, $X_{TCSCref}$ is the reference reactance of TCSC, K_T and T_T are the gain and time constant of the TCSC. U_{TCSC} is the output of conventional lead-lag TCSC damping stabilizer.

Since the TCSC damping controllers are installed in series with the transmission lines, in order to damp the inter-area oscillations, local signals which carry valuable information are always preferred as input signals [11], [12]. Hence, in this paper, the transmission line active power has been considered as an input signal for TCSC damping controller design. To identify the appropriate location for installing the TCSC, base case power flow is carried out and the results are provided in

Table II. Base on the results, it is observed that the power flow in line 4-9 is very high and it is the longest line in the system under study. This demonstrates that, the line 4-9 is the best location to install TCSC controller which has been considered in this paper. However, the bus no 4, which is much closer to large generator G_1, is more suitable to install SVC [14].

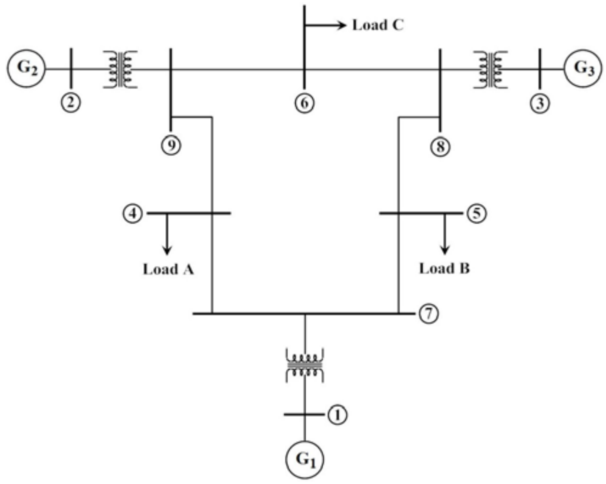

Fig. 1 Three-machine nine-bus power system

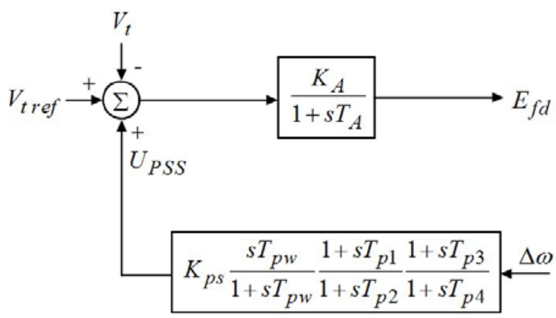

Fig. 2 Conventional excitation system with PSS

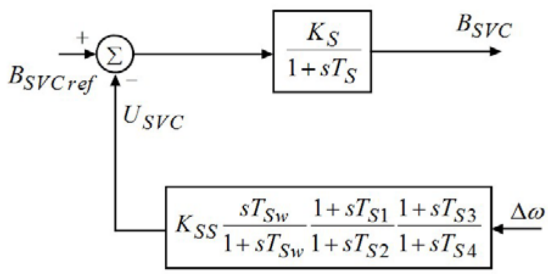

Fig. 3 Structure of the SVC damping controller

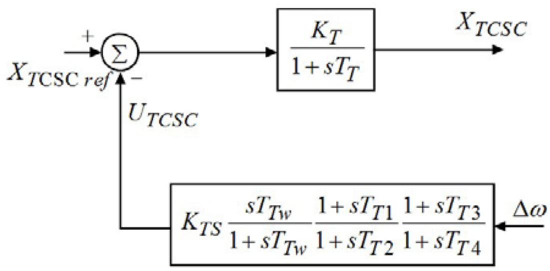

Fig. 4 Structure of the TCSC damping controller

TABLE I
DIFFERENT LOADING CONDITIONS APPLIED TO THE TEST SYSTEM

	Nominal		Heavy		Light	
	P	Q	P	Q	P	Q
Generator						
G_1	0.6908	0.3241	0.7758	0.6937	0.4609	-0.1039
G_2	1.6300	0.1076	2.4450	0.5063	0.8150	-0.2051
G_3	0.8500	-0.0909	1.2750	0.1662	0.4250	-0.2412
Load						
A	1.25	0.50	1.90	0.75	0.65	0.25
B	0.90	0.30	1.30	0.45	0.45	0.15
C	1.00	0.35	1.50	0.50	0.50	0.17

TABLE II
BASE CASE POWER FLOW ON 100-MVA BASE

From bus	To Bus	Real power flow (p.u)
7	4	0.2438
4	9	0.9847
9	6	0.6132
6	8	0.3864
8	5	0.4617
5	7	0.4436

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) based objective function is considered only error, 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 [22]. 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

$$J = \int_0^t t\,[|\Delta\omega_2 - \Delta\omega_1| + |\Delta\omega_3 - \Delta\omega_1|]\,dt \qquad (12)$$

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

In order to maintain stability and to provide efficient damping, it is aimed to minimize the objective function. To reduce the computational burden in this study, the value of the wash out time constant T_w is fixed at 5s, and the values of T_2, and T_4 of the all damping controllers (i.e. for PSSs, SVC and TCSC damping controllers) are kept constant at 0.05s. Tuning of T_1 and T_3 are chosen to achieve the net phase lead required by the system. Therefore, the optimization problem is formulated as:

Minimize '*J*' such that to satisfy the following inequality constraints,

$$K_S^{\min} \le K_S \le K_S^{\max} \tag{13}$$

$$T_1^{\min} \le T_1 \le T_1^{\max} \tag{14}$$

$$T_3^{\min} \le T_3 \le T_3^{\max} \tag{15}$$

where K_S represents gain of damping stabilizer block, and T_1,T_2,T_3,T_4 are the time constants of lead-lag blocks in the damping controllers.

In this study, the coordinated controller parameters of PSS, TCSC as well as SVC damping controller is optimized based on the objective function given in (14) using advanced adaptive PSO described in section III. The flow chart of AAPSO algorithm based coordinated design of PSS with TCSC and SVC damping controller is depicted in Fig. 5. The ranges of optimal parameter are [0.01 – 50] for K_S, and [0.06 – 1] for T_1 and T_3. The washout time T_w is set as 5.

V. OPAL-RT Hardware Simulator

OPAL-RT hardware simulator is a distributed Real-time platform that enables engineers to conduct Real-time Simulation with Hardware-in-the-Loop, in a very short time, at a low cost [23]. It is flexible enough to be applied to the most complex simulation and control problem, whether it is a Real-time Hardware-in-the-Loop application or for speeding up model execution, control and test. RT-LAB allows the user to readily convert MATLAB models, via Real-time workshop (RTW), and then to conduct Real-time simulation of those models executed on multiple target computers equipped with multi-core PC processors. This is used particularly for Hardware-in-loop (HIL) and rapid control prototyping applications [24]. RT-LAB transparently handles synchronization, user interaction, and real world interfacing using I/O boards and data exchanges for seamless distributed execution

In single target configuration (Fig. 6), typically used for rapid control prototyping, a single computer runs the plant simulation or control logic. One or more hosts may connect to the target via an Ethernet link. The target uses QNX or Linux as the RTOS for fast simulation or for applications where real-time performance is required. RT-LAB used RedHat ORT which is the standard Red Hat distribution package with an optimized set of parameters to reach real-time performance enabling to reach model time step as low as 10 micros on multi-core processors. The laboratory setup of OPAL-RT hardware simulator is shown in Fig. 7 (a).

The OP5142 reconfigurable board, which is shown in Fig. 7(b)., is one of the key building blocks in the modular OP5000 I/O system from Opal-RT Technologies [25]. It allows the incorporation of FPGA technologies in RT-LAB simulation clusters for distributed execution of HDL functions and high-speed, high -density digital I/O in Real-time models. The OP5142 platform FPGA device can be configured exactly as required by the user. Integration with MATLAB, the System Generator for DSP toolbox from Xilinx and RT-XSG from Opal-RT Technologies allows the transfer of MATLAB models to the OP5142 FPGA processor for distributed processing.

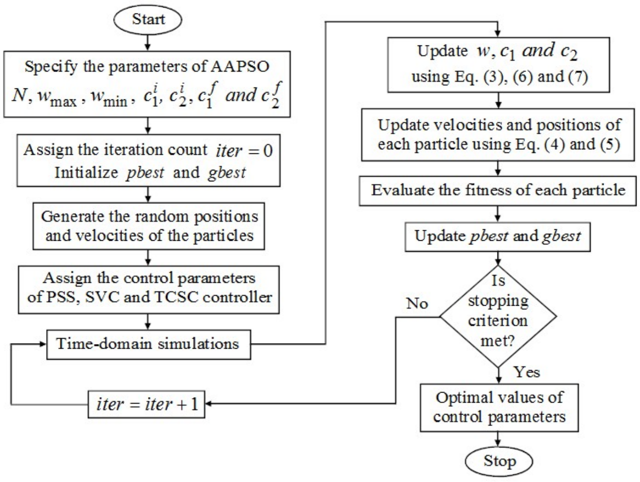

Fig. 5 Flow chart of coordinated designing using advanced adaptive PSO

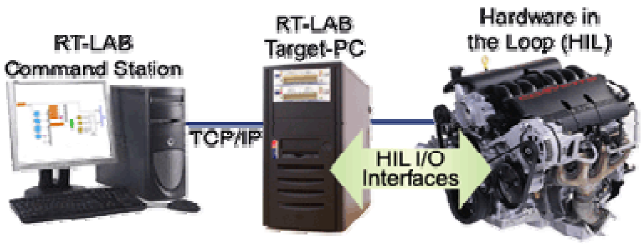

Fig. 6 RT-LAB simulator with single target system and HIL

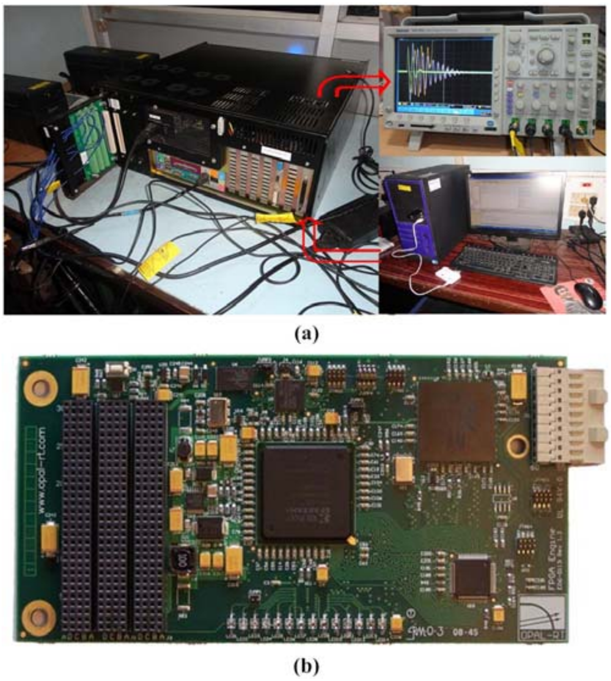

Fig. 7 (a) Laboratory setup of OPAL-RT hardware simulator, (b) The OP5142 Reconfigurable board

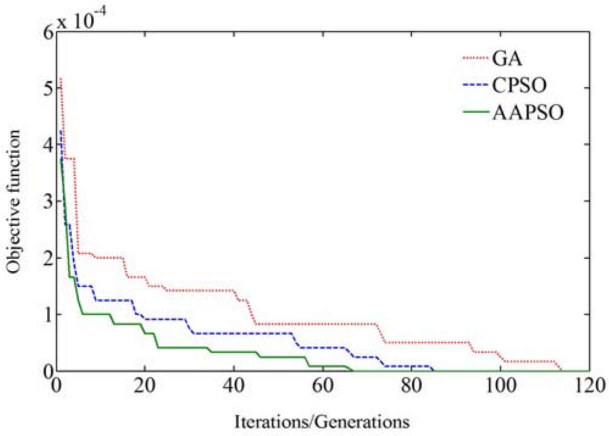

Fig. 8 Objective function characteristics of different algorithms

VI. System Dynamic Performance in Real-Time

In this analysis the three-machine nine-bus system is considered. The PSSs installed at generators G_2, G_3 and a simple exciter installed at generator G_1. The power flow in line 4-9 is the largest in the test system and this line is the longest line too [12]. Hence, the best location to install TCSC is in series with the line 4-9 is considered in this study. However, the bus no 4, which is much closer to generator G1, is more suitable to install SVC [14]. The non-linear model simulation is carried out using MATLAB programming for a three phase fault. The fault is applied at bus 9 and cleared by tripping the line 9-6 permanently. The fault applied at 1 sec. and cleared at 1.1sec (i.e. a six cycle fault is applied to the system). Four control schemes employed to the test system to compare the performance of the proposed coordinated controller. In addition to this, we validated the proposed controller real-time by implementing in OPAL-RT hardware simulator.

The comparison over the performances of GA, CPSO and AAPSO for the objective function convergence is shown in Fig. 8. To operate all these optimization algorithms at equal complexities, we considered 120 iterations/generations and each of it consists of 100 individuals. It is clearly observed from Fig. 8, AAPSO had fast convergence rate over CPSO and GA. In this paper, the objective function convergence value is fixed at 1e-5. Here, the AAPSO reaches its convergence value near about 67 iterations, whereas CPSO takes approximately 84 iterations and GA takes more than 112 iterations. Hence, the average time taken for convergence of solution is less using AAPSO compared to CPSO and GA. The optimal parameters of coordinated controller are obtained through AAPSO and the values are given in Table III.

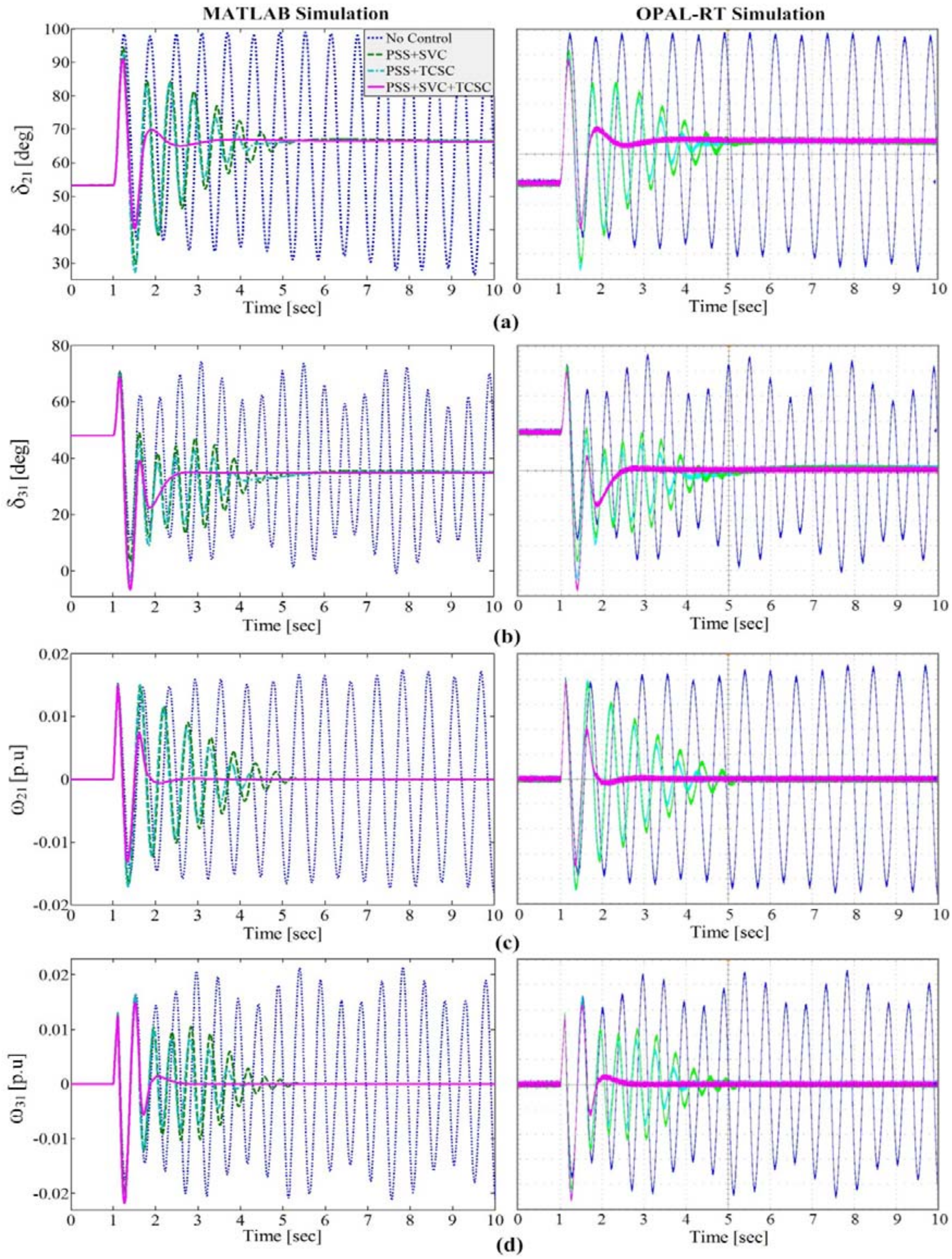

Fig. 9 Response of test system for nominal loading (a) angle change δ_{21} (b) angle change δ_{31} (c) speed change ω_{21} (d) speed change ω_{31}

A. Nominal Loading Condition

The effectiveness of proposed coordinated controller is tested with the test system under nominal loading. Fig. 9 represents the performance of test system for nominal loading. In Figs. 9 (a), and (b), represents rotor angle variations δ_{21} and δ_{31} respectively. Similarly (c) and (d) represents variation in speed ω_{21} and ω_{31}. In each Fig. (a), (b), (c) and (d) both simulation results and real-time results are compared. The results shows the oscillations are not damped in case of system without controller due to the large disturbance. Whereas the coordinated controller shows better damping effect to power oscillations when compare with other control schemes. The settling time of these oscillations are also very good for the system having coordinated controller.

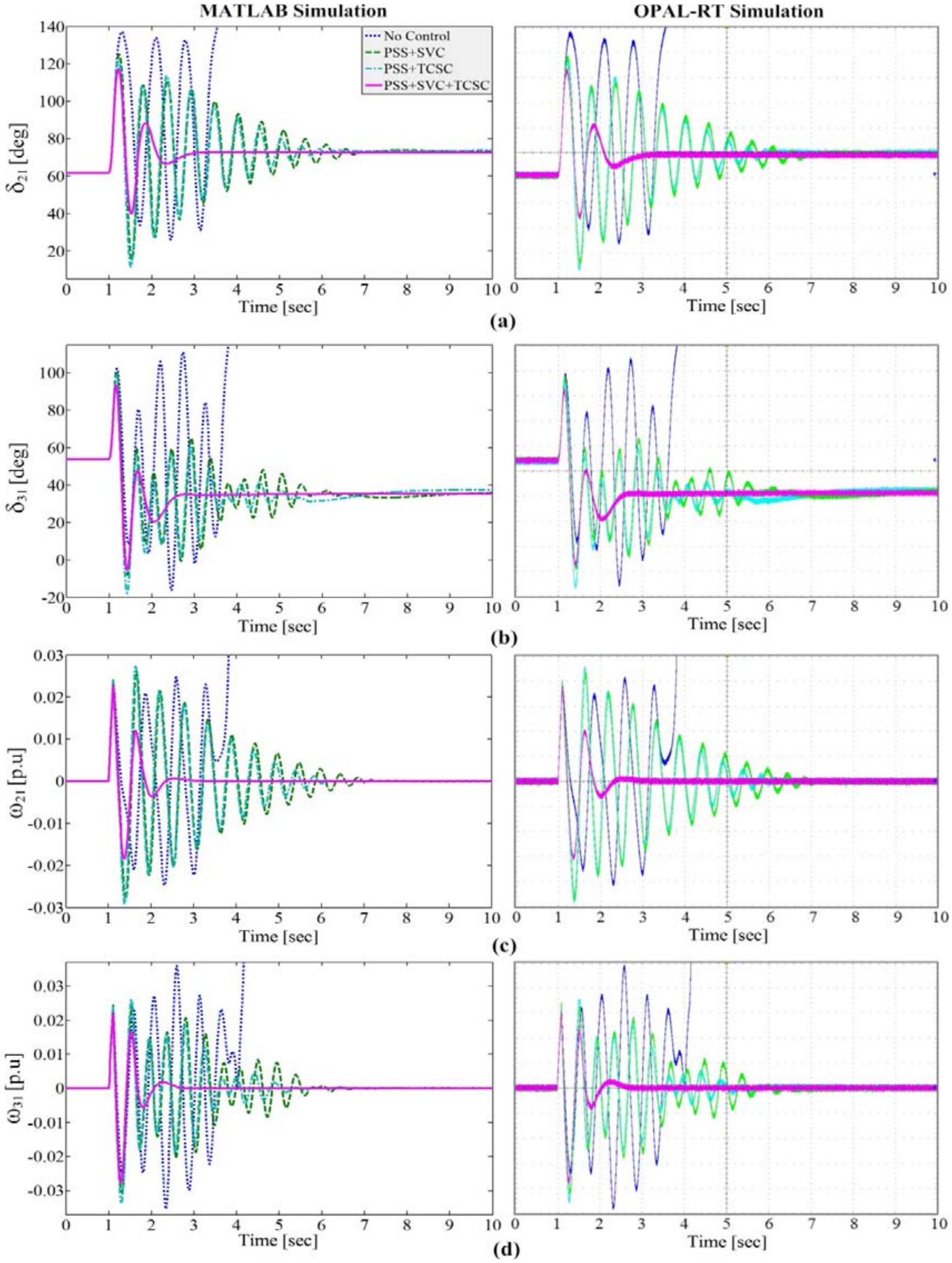

Fig. 10 Response of test system for heavy loading (a) angle change δ_{21} (b) angle change δ_{31} (c) speed change ω_{21} (d) speed change ω_{31}

B. Heavy Loading Condition

To test the robustness of proposed coordinated controller the test system is operated even in heavy loading condition. Here, all the loads and real powers of generators G_2, G_3 are increased 50% more than that of the nominal loading condition. Fig. 10 shows the performance of test system in MATLAB simulation as well as the OPAL_RT hardware simulator for heavy loading. From the results the test system without any controller unstable and the generators are loses their synchronism. However the test system with coordinated controller shows better damping as well as adequate settling time compared with other control schemes. In heavy loading condition also the proposed controller performs well in all aspects.

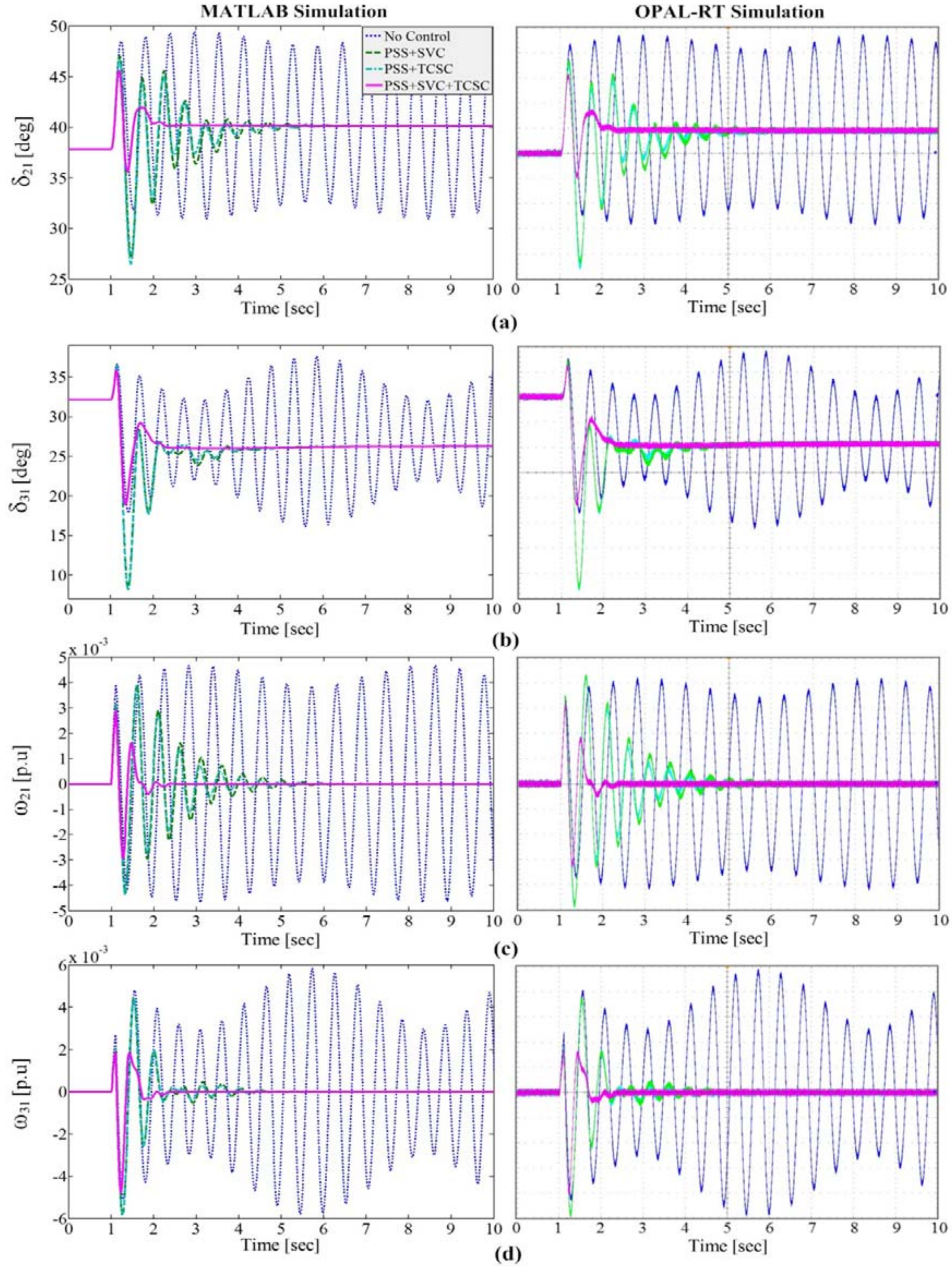

Fig. 11 Response of test system for light loading (a) angle change δ_{21} (b) angle change δ_{31} (c) speed change ω_{21} (d) speed change ω_{31}

TABLE III
OPTIMAL CONTROL PARAMETERS OBTAINED USING AAPSO ALGORITHM

Control parameters	PSS2	PSS3	SVC	TCSC
K_S	8.6027	5.3861	1.2563	1.0248
T_1	0.6270	0.4713	0.5401	0.5024
T_2	0.0378	0.0412	0.0216	0.0251
T_3	0.8061	0.6347	0.3215	0.4577
T_4	0.0411	0.0219	0.0340	0.0324

C. Light Loading Condition

Fig. 11 shows the performance of test system for light loading. Here, all the loads and real powers of generators G_2, G_3 are decreased 50% less than that of the nominal loading condition. It is found that in light loading condition, all generators are operated in leading power factor. The power oscillations damp out quickly with the proposed coordinated controller compared with other controller schemes. However the test system with no controller unable to damp out the oscillations. Hence, the robustness of proposed coordinated damping controller tested in three different loading conditions. It gives acceptable damping effect and adequate settling time for power oscillations under severe disturbance. Finally, in each loading condition the simulation results are well examined with real-time hardware results.

VII. CONCLUSION

In this paper, a robust coordinated design of PSS with SVC and TCSC damping controller in multi-machine power system is proposed. The controller design is formulated as an optimization problem and an objective function based on ITAE is minimized using AAPSO. The optimal control parameters of coordinated controller are obtained at the end of AAPSO algorithm. Four different control schemes are employed on the test system to investigate the performance of the proposed controller. 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 different loading conditions for a large disturbance. The simulation results are validated with implementation in real-time on OPAL-RT hardware. The simulation results as well as OPAL-RT real-time results show that the test system dynamic performance and overall damping effect are enhanced by simultaneous coordinated design of PSS with SVC and TCSC damping controller.

APPENDIX

a). In this work, the i^{th} machine model is given as follows [2]:

$$\dot{\delta}_i = \omega_i - \omega_0 \quad \text{(A1)}$$

$$\dot{\omega}_i = -\frac{D_i}{2H_i}\left[\omega_i - \omega_0\right] + \frac{\omega_0}{2H_i}\left[P_{mi} - P_{ei}\right] \quad \text{(A2)}$$

$$\dot{E}'_{qi} = \frac{1}{T^1_{d0i}}\left[E_{fdi} - (X_{di} - X'_{di})I_d - E'_{qi}\right] \quad \text{(A3)}$$

b). System data for three-machine nine-bus power system [2]: all data in p.u. on a 100-MVA base

$$H_1 = 23.64,\ H_2 = 6.40,\ H_3 = 3.01,\ X_{d1} = 0.1460,$$
$$X_{d2} = 0.8958,\ X_{d3} = 1.3125,\ X'_{d1} = 0.0608,$$
$$X'_{d2} = 0.1198,\ X'_{d3} = 0.1813,\ X_{q1} = 0.0969,$$
$$X_{q2} = 0.8645,\ X_{q3} = 1.2578,\ T'_{d01} = 8.96,$$
$$T'_{d02} = 6.00,\ T'_{d03} = 5.89$$

Exciter: $K_{A1} = K_{A2} = K_{A3} = 20,\ T_{A1} = T_{A2} = T_{A3} = 0.05s$

SVC Controller: $K_S = 20, T_S = 0.02s$

TCSC Controller: $K_T = 20, T_T = 0.02s$

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Rajendraprasad Narne was born in Andhra Pradesh, India on November 21 1985. He received his B.Tech. degree in Electrical and Electronics Engineering from JNTU Hyderabad, India, in 2007, and the M .E. Degree in Power System Engineering from Anna University, India in 2009. Currently, he is working towards his Ph.D. degree at National Institute of Technology, Rourkela, Orissa, India, under the supervision of Prof. P.C.Panda. His research interests include power system stability and control, and FACTS controllers.

Prafulla Chandra Panda (SM'05) was born in Orissa on November 01, 1948. He received his B.Sc., M.Sc., and Ph.D. degrees, all in electrical engineering from Sambalpur University, Orissa, India, in the year 1971, 1974 and 1990 respectively.

Since 1977, he has been with National Institute of Technology, Rourkela, Orissa, India, where he is now a professor. He is senior member of IEEE and Fellow of IE (India). At present, his research interests include Power system dynamic stability analysis, FACTS Controllers and High voltage dc transmission.