CHAPTER 5

SYSTEM STUDIES

5.1 INTRODUCTION

This chapter presents a novel knowledge domain states mapping concept for intelligent power flow control. The proposed power control has been derived from the controller parameters selection, corresponding to changing operating conditions, which are mapped in knowledge domain structure as a set corresponding to respective operational shift. The knowledge domain has been built utilizing intelligent optimal heuristic algorithms; the controller parameters thus obtained corresponding to operational shift adequately provides the design basis of all power controllers considered in the thesis. The proposed concept is generalized and can be used to design any controller in a very large interconnected power network. It has been shown that adequate knowledge domain and linked inference mechanism which update /modulate the controller parameters provide an excellent tracking performance under perturbation and thus overall system stability is ensured. A detailed system studies with proposed concept has been attempted for three multi-area interconnected sample power systems. It has been observed that under changing operating conditions such as load change / change in transmission line length, controller effectively modulates the power flow as desired and quickly damps local as well as inter-area oscillations. It has also been demonstrated that in situations of improper response of the tuned controller, the inference mechanism successfully inducts suitable additional controller in system as supplementary control strategy, and thus helps to recover overall system at earliest. This concept has been viewed as control shifting and control sharing strategy depending on the system operational shift. This chapter provides complete hierarchical control structure along with control shifting/sharing concept which has been widely tested through extensive simulation to gain the confidence in design. The controllers included in study are Power System Stabilizers (PSS) and FACTS (STATCOM, SSSC and (UPFC) devices.

5.2 KNOWLEDGE DOMAIN MAPPING BASED CONTROL STRUCTURE

Knowledge domain states mapping concept is used to tune the control parameters of PSS and FACTS devices under various system operating conditions. The first part of this hierarchical control structure includes proper tuning of the local controller (PSS), which is termed as controller parameter up-gradation to result in effective oscillation damping. While retuning the controllers, parameters of controllers are up-graded according to operational shift, and thus retuned parameters are inducted in controller structure to provide effective oscillation damping. In situations of limited capacity of the parameters adjustment, additional standby similar controller architecture may be incorporated apart from the existing one; this is termed as controller shifting to arrive at smooth power flow control. The control sharing concept has been proposed in situations when existing controller’s extended parametric domain is non-responsive for a given perturbation, thus additional controller is inducted retaining old controller to assist the control. This has been viewed as the onset of existing controller stable domain is reached; the new control is inducted for taking up remaining perturbation, thus both old and new cooperates and coordinates the control strategy and stabilizes the system without delay. Three optimization techniques (FA, GSA and PSO) have been used to develop knowledge domain structure for local as well as the global controllers suitably placed in the system. The complete control structure has been shown in Figure 5.1.

5.2.1 Control Parameter Up-gradation Concept

Control parameter up-gradation concept includes the optimal retuning of PSS controllers, as operational shift occurs in system. Three optimization techniques (GSA, FA and PSO) have been used to develop knowledge domain structure for all the controllers (PSS and FACTS devices) connected in system. Different sample test systems have been considered to demonstrate the effectiveness of concept. Two types of operational shift have been taken in study; one is the change in load demand, and other is the variation in length of transmission line.

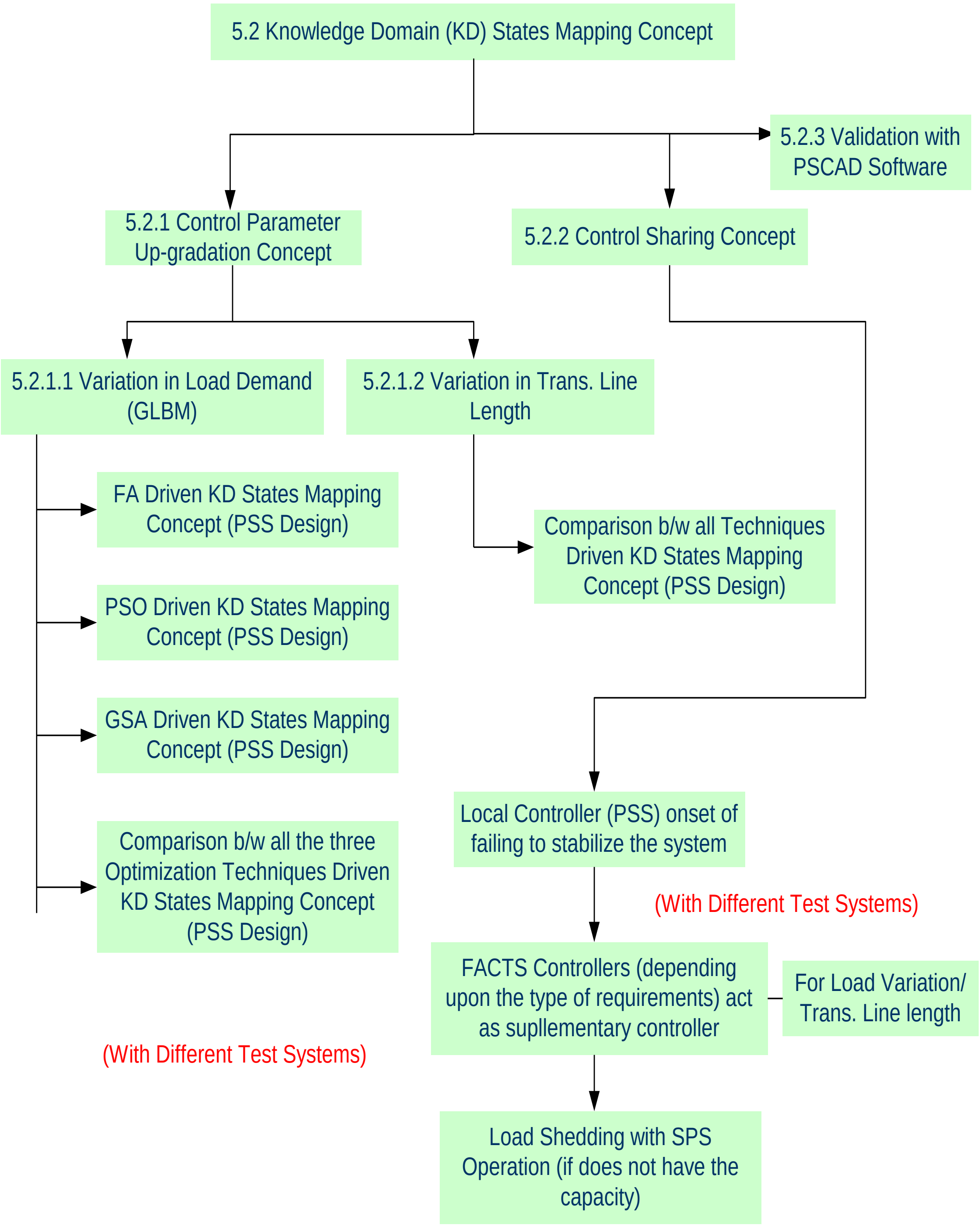


Figure 5.1 Layered structure of knowledge domain based hierarchy of control

5.2.1.1 Variation in Load Demand

Firefly Algorithm Driven Knowledge Domain States Mapping Concept - PSS Design

A sample six area test system (Figure 5.2) with UPFC connected between area 2 and area 3 and PSS to all generators has been developed. Firefly Algorithm (FA) has been used to develop knowledge domain for control parameters of PSS by minimizing ITAE as objective function. Three cases have been considered for finding the system response with proposed concept. In each case load has been changed after some time, and accordingly after some switching delay (Tsd=0.1 sec) controller's parameters are up-gradated to a new value from Knowledge Domain Inference Mechanism (KDIM) for respective load change intelligently.

CASE 5.1-Load L1 at time t_1 and then L2 at time t_2

CASE 5.2-Load L1 at time t_1 and then L3 at time t_3

CASE 5.3-Load L1 at time t_1 then L4 at time t_4 and then L5 at time t_5

Where L1=2.923, L2=2.365, L3=0.223, L4=2.434, L5=0.565 and t_1=0 sec, t_2=1 sec, t_3=2 sec, t_4=1.5 sec, t_5=4 sec. These load variations occur in area 6, so perturbation response of the most affected area (Area 6) has been shown in results. Here L is susceptance (B) of the load with conductance G=1.8.

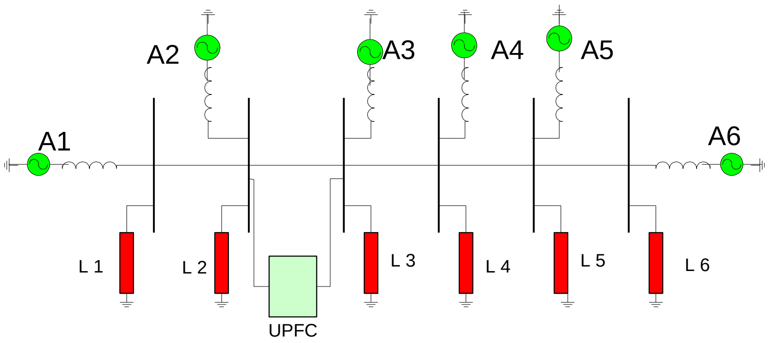


Figure 5.2 Sample Six Area test system 1

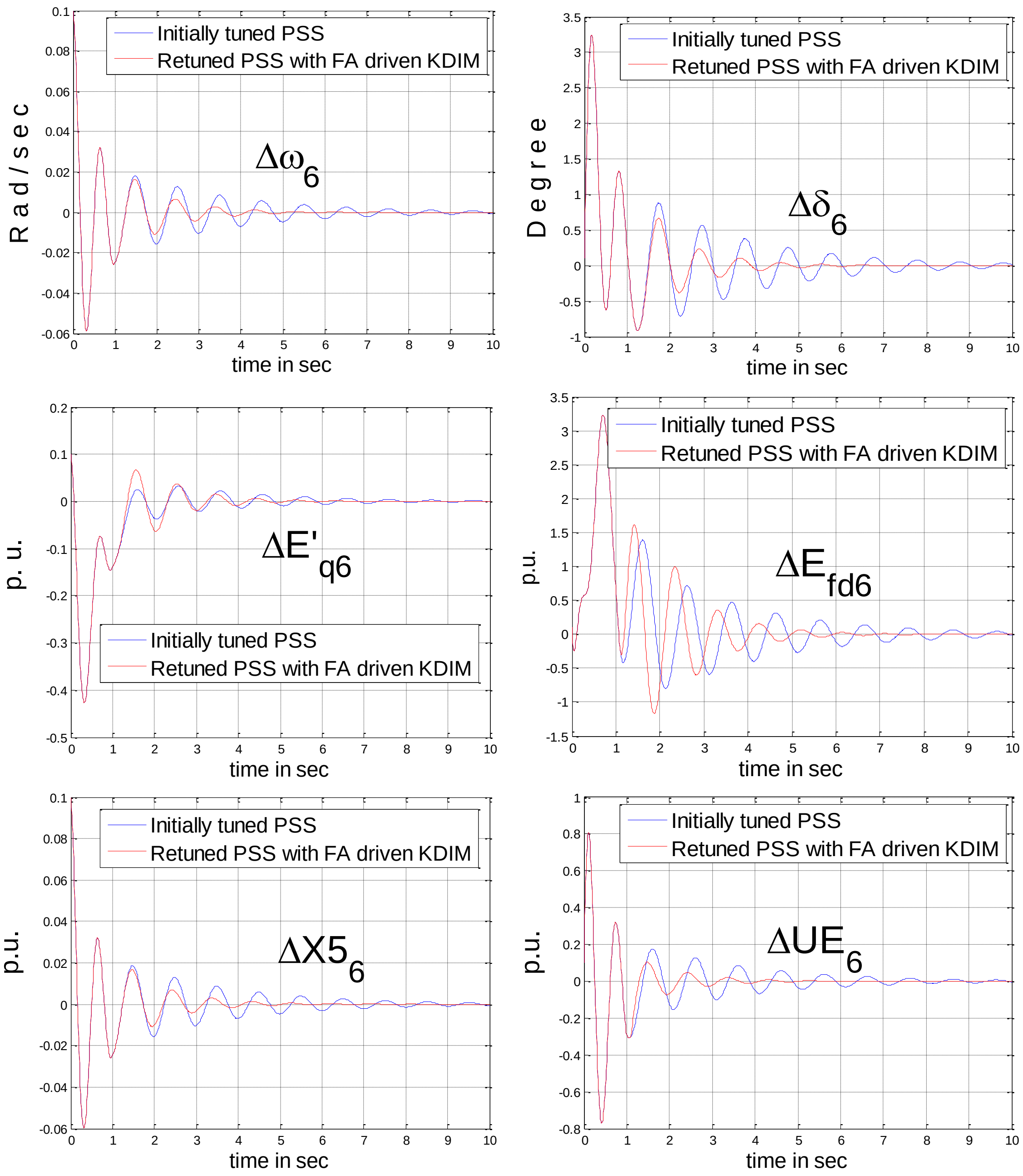
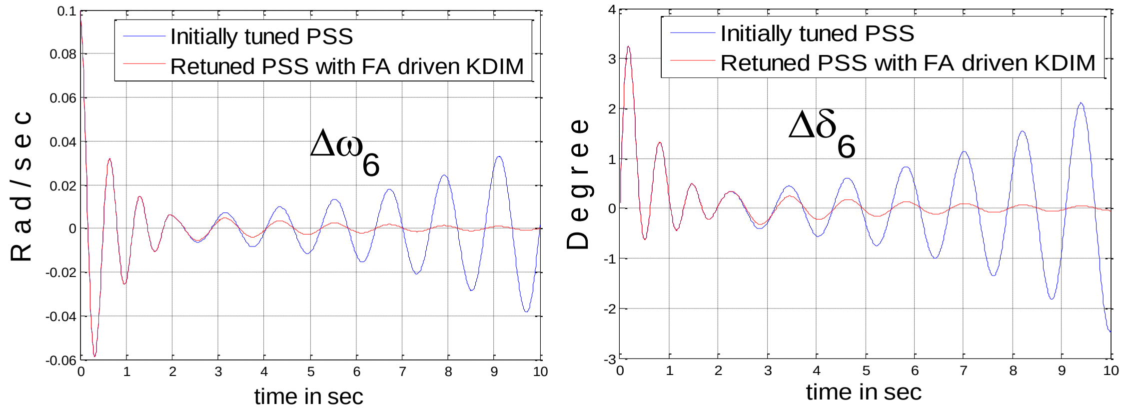


Figure 5.3 Perturbed responses for Area 6 with proposed concept (FA driven KDIM) for Case 5.1



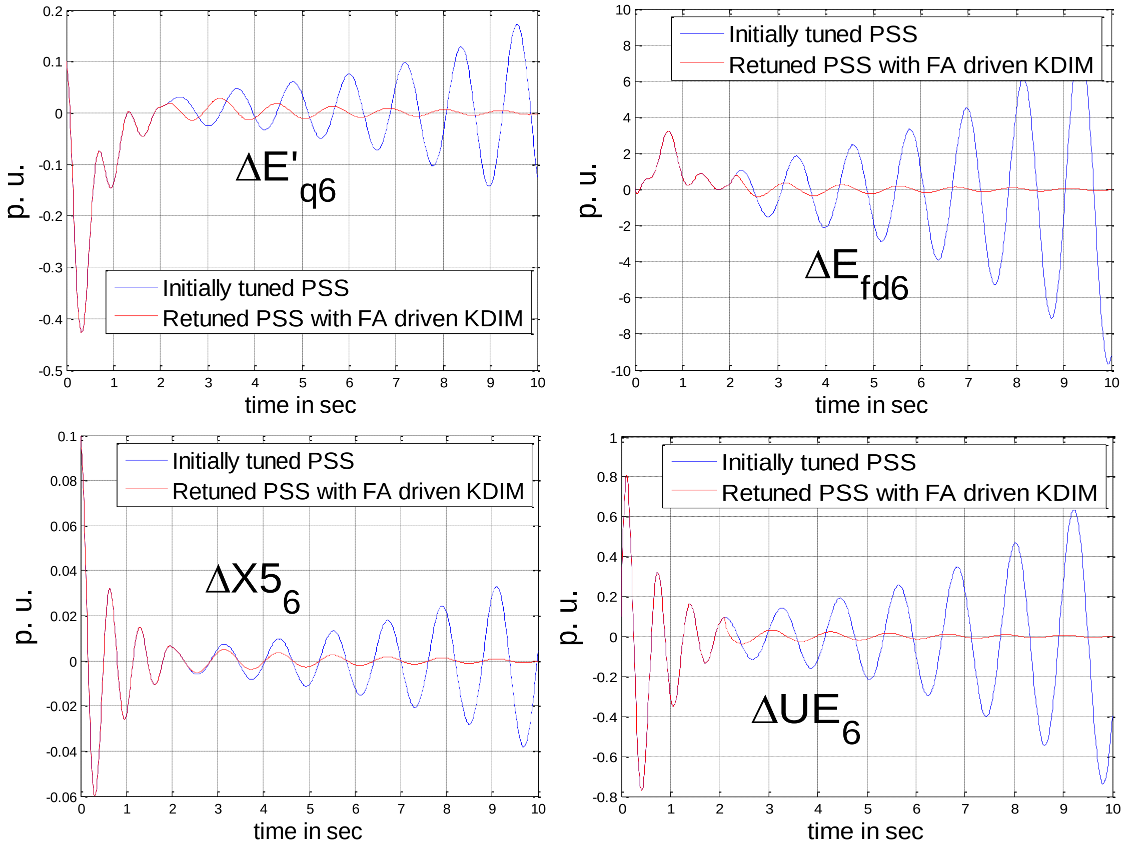
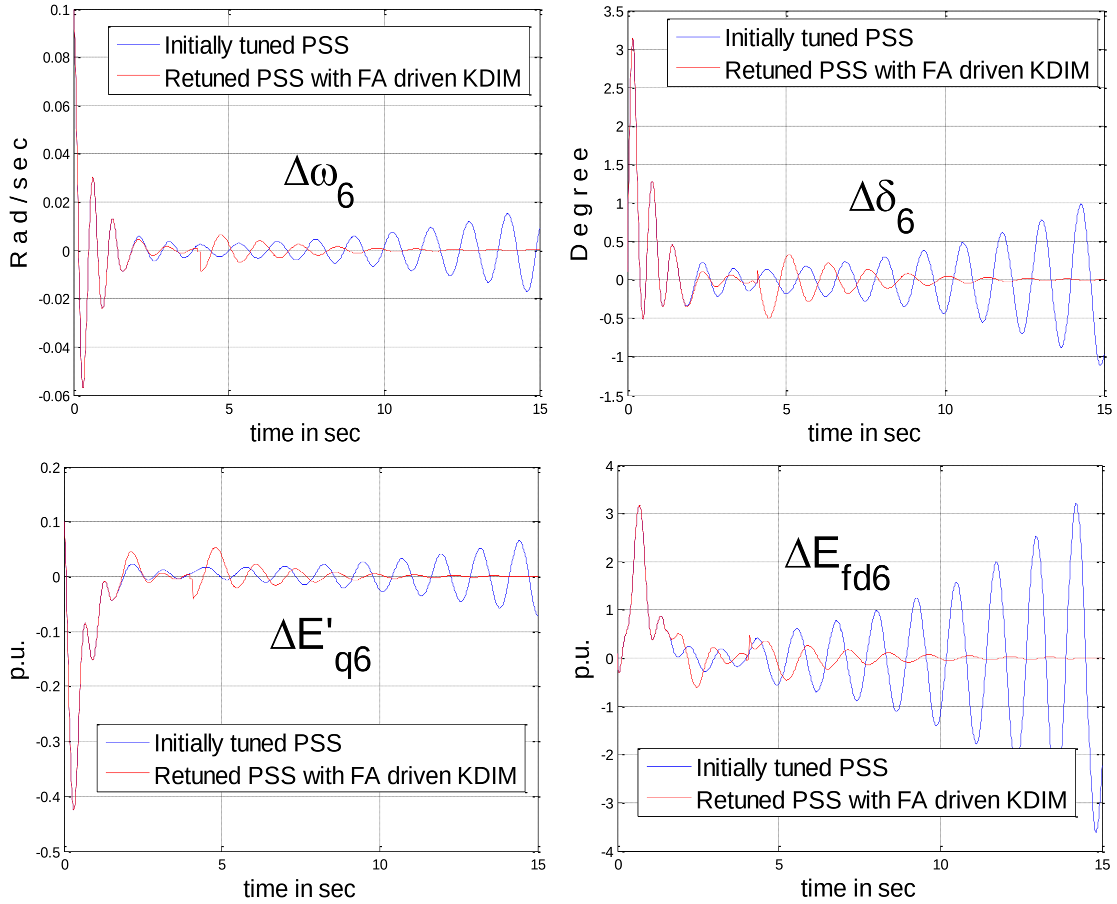


Figure 5.4 Perturbed responses for Area 6 with proposed concept (FA driven KDIM) for Case 5.2



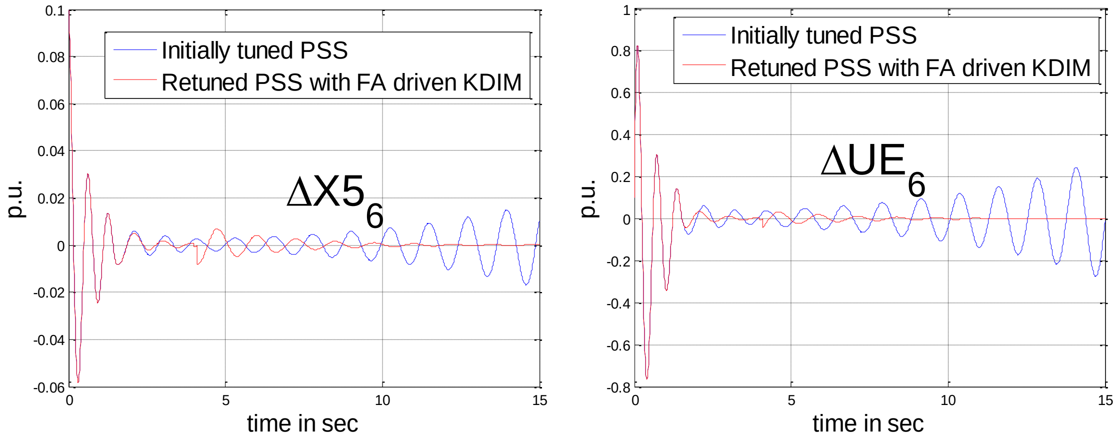


Figure 5.5 Perturbed responses for Area 6 with proposed concept (FA driven KDIM) for Case 5.3

Table 5.1(a) Comparison in system responses for Area 6 with all the three cases (Case 5.1, 5.2 and 5.3)

System	States	O.S.	S.T.	Eigenvalues 1.0e+03*
CASE 5.1 Initially tuned PSS as load change T61=0.0169; T62=0.1792; (at L1)	$\Delta\omega_6$	0.019	9.8	-0.0004 + 0.0062i
	$\Delta\delta_6$	0.90	10.5	-0.0004 - 0.0062i
	$\Delta E'_{q6}$	0.30	8.9	-0.0004
	ΔE_{fd6}	1.40	10.5	-0.0032
	$\Delta X5_6$	0.02	9.6	-0.0038 + 0.0037i
	ΔUE_6	0.19	9.3	-0.0038 - 0.0037i
CASE 5.1 Retuned PSS with FA driven KDIM as load change T61= 0.0353; T62= 0.0471; (at L2)	$\Delta\omega_6$	0.017	4.5	-0.0009 + 0.0066i
	$\Delta\delta_6$	0.65	5.1	-0.0009 - 0.0066i
	$\Delta E'_{q6}$	0.60	5.5	-0.0003
	ΔE_{fd6}	1.40	6.4	-0.0021 + 0.0032i
	$\Delta X5_6$	0.016	4.5	-0.0021 - 0.0032i
	ΔUE_6	0.10	4.1	-0.0080
CASE 5.2 Initially tuned PSS as load change T61=0.0169; T62=0.1792; (at L1)	$\Delta\omega_6$	0.012	U.S.	0.0003 + 0.0053i
	$\Delta\delta_6$	0.5	U.S.	0.0003 - 0.0053i
	$\Delta E'_{q6}$	0.04	U.S.	-0.0054 + 0.0025i
	ΔE_{fd6}	1.1	U.S.	-0.0054 - 0.0025i
	$\Delta X5_6$	0.01	U.S.	-0.0004
	ΔUE_6	0.1	U.S.	-0.0008
CASE 5.2 Retuned PSS with FA driven KDIM as load change T61= 0.0644;T62= 0.1248; (at L3)	$\Delta\omega_6$	0.005	9.5	-0.0213
	$\Delta\delta_6$	0.25	9.4	-0.0003 + 0.0053i
	$\Delta E'_{q6}$	0.02	8.9	-0.0003 - 0.0053i
	ΔE_{fd6}	0.9	9.2	-0.0003
	$\Delta X5_6$	0.007	9.8	-0.0021
	ΔUE_6	0.1	7.1	-0.0028
CASE 5.3 Initially tuned PSS as load change T61=0.0169; T62=0.1792; (at L1)	$\Delta\omega_6$	0.004	U.S.	-0.0001 + 0.0052i
	$\Delta\delta_6$	0.2	U.S.	-0.0001 - 0.0052i
	$\Delta E'_{q6}$	0.025	U.S.	-0.0004
	ΔE_{fd6}	0.5	U.S.	-0.0026 + 0.0004i
	$\Delta X5_6$	0.004	U.S.	-0.0026 - 0.0004i
	ΔUE_6	0.07	U.S.	-0.0080
CASE 5.3 Retuned PSS with FA driven KDIM as load change T61=0.0644;T62=0.1248;(at L4) T61=0.0392;T62=0.0471;(at L5)	$\Delta\omega_6$	0.008	11.0	-0.0213
	$\Delta\delta_6$	0.4	12.5	-0.0004 + 0.0050i
	$\Delta E'_{q6}$	0.05	10.5	-0.0004 - 0.0050i
	ΔE_{fd6}	0.6	12.2	-0.0003
	$\Delta X5_6$	-0.009	11.2	-0.0024 + 0.0014i
	ΔUE_6	-0.004	9.0	-0.0024 - 0.0014i

In Table 5.1(a), following notation has been adopted: K.D.I.M.= Knowledge Domain Inference Mechanism, O.S.= Overshoot, S.T.= Setting Time and U.S.=Unstable System.

In Figures 5.3 - 5.5, perturbed response for all states with proposed concept are compared with the response, when controller settings are unchanged. The proposed concept demonstrates that as system operating condition changes with time, retuning of respective control parameters from the knowledge domain inference mechanism not only improves oscillation damping but also performs relatively better. The results reflect that overshoot/ undershoot and settling time of state variables is greatly reduced by proposed concept with retuning of controllers. For various cases, oscillations in the system increases with initially tuned values and damped out very quickly with retuning of controller with proposed method. Table 5.1(a) shows the overshoot for each case at the time of final load change (i.e., for case 1, overshoot and eigenvalues are after time t_2, similarly for case 3 overshoot and eigenvalues are after time t_5) and settling time is for overall system response. Table 5.1(b) represents the eigenvalues of the entire sample test system from which complete behavior of system can be understood as all the eigenvalues are placed towards the left-hand side of complex plane.

Table 5.1(b) Eigenvalue of Sample Six Area test system

Area 1 *1.0e+3	**Area 2 *1.0e+3**	**Area 3 *1.0e+3**	**Area 4 *1.0e+3**	**Area 5 and Area 6 *1.0e+3**
-0.0003	-0.0004	-0.0099 + 0.0034i	-0.0004 + 0.0062i	-2.5922
-0.0005 + 0.0062i	-0.0125	-0.0099 - 0.0034i	-0.0004 - 0.0062i	-1.2860
-0.0005 - 0.0062i	-0.0004 + 0.0049i	-0.0013 + 0.0038i	-0.0004	-0.2635 + 0.1427i
-0.0039 + 0.0054i	-0.0004 - 0.0049i	-0.0013 - 0.0038i	-0.0032	-0.2635 - 0.1427i
-0.0039 - 0.0054i	-0.0022 + 0.0052i	-0.0003	-0.0038 + 0.0037i	-0.2630
-0.0025	-0.0022 - 0.0052i	-0.0015	-0.0038 - 0.0037i	-0.0094
				-0.0014
				-0.0026

Another case study with six area test system as shown in Figure 5.6 has been carried out to demonstrate the flexibility of the knowledge domain states mapping concept.

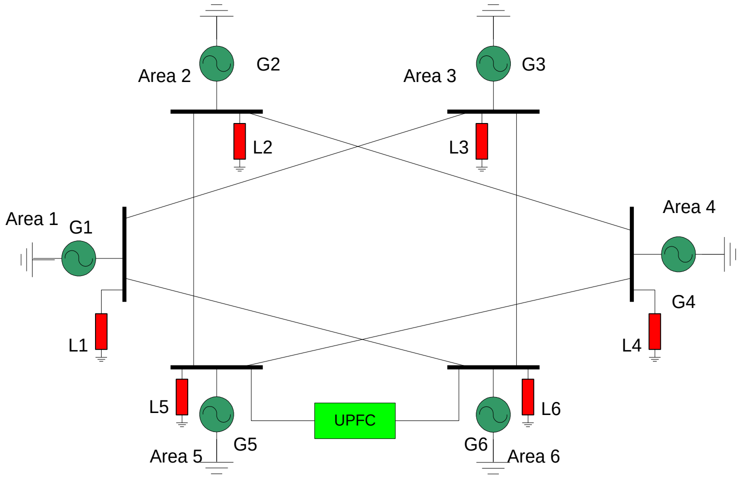


Figure 5.6 Sample Six Area test system 2

CASE 5.4- Load L3(1) at time t_1 and then L3(2) at time t_2, Where initial load in area 3 is L3(0). (Where L3(0)=G3(0)+jB3(0)), G3(0)=1.6615; B3(0)=1.9029; and L3(1)=1.4*L3(0), L3(2)=0.6*L3(0); t_1=0 sec, t_2=1.5 sec, G is the conductance and B is the susceptance of the load.

CASE 5.5- Load L5(1) at time t_1 and then L5(2) at time t_2, Where initial load in area 5 is L5(0). (Where L5(0)=G5(0)+jB5(0)), G5(0)=1.0786; B5(0)=1.0028;and L5(1)=0.5*L5(0), L5(2)=1.0*L5(0); t_1=0 sec, t_2=2.5 sec. Comparison has been made for this case study with the tuning of PSS using Genetic Algorithm (GA) by taking two objective functions which are based on eigenvalues (J1) [67], and ITAE performance indices (J2).

$$J1 = \max\{\mathrm{Re}(\lambda_{k,i} + \beta)\} \tag{5.1}$$

$$J2 = J\{e(t)\} = \int_0^\infty t \times |e(t)|\, dt \tag{5.2}$$

Here $\lambda_{k,i}$ is the i^{th} closed loop eigenvalue of k^{th} plant and β is the relative stability. e(t) is the error of the state variables from their desired values.

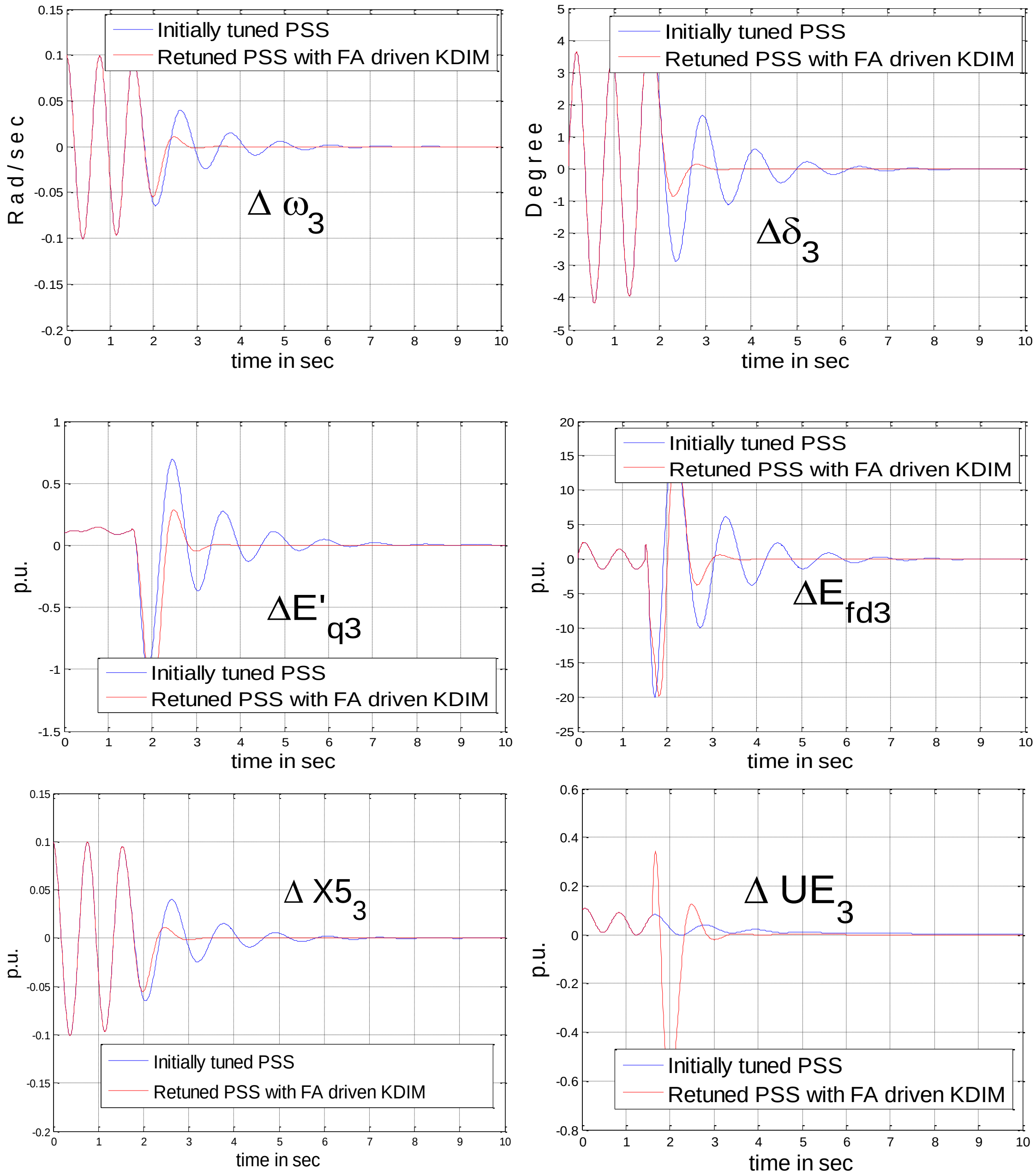
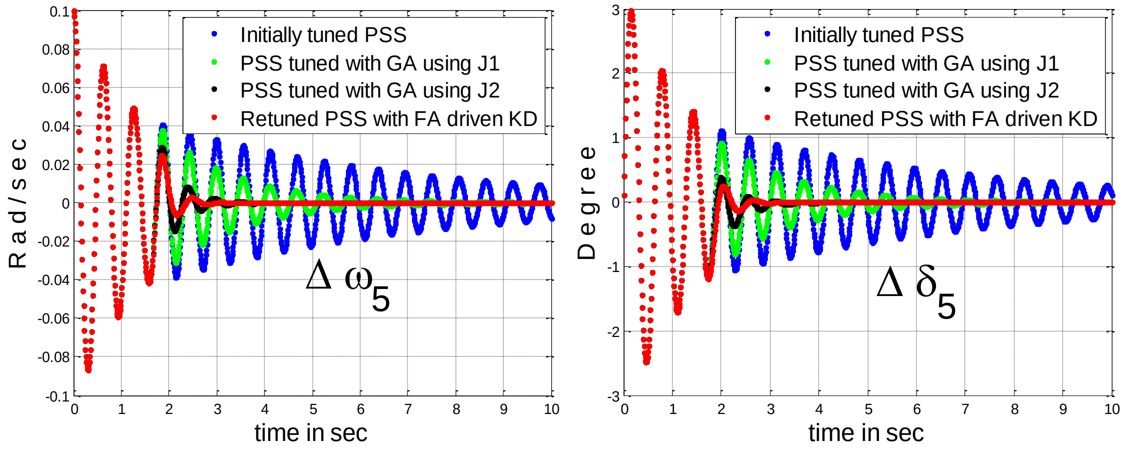


Figure 5.7 Perturbed responses of Area 3 with proposed concept (FA driven KDIM) for Case 5.4 (only PSS)



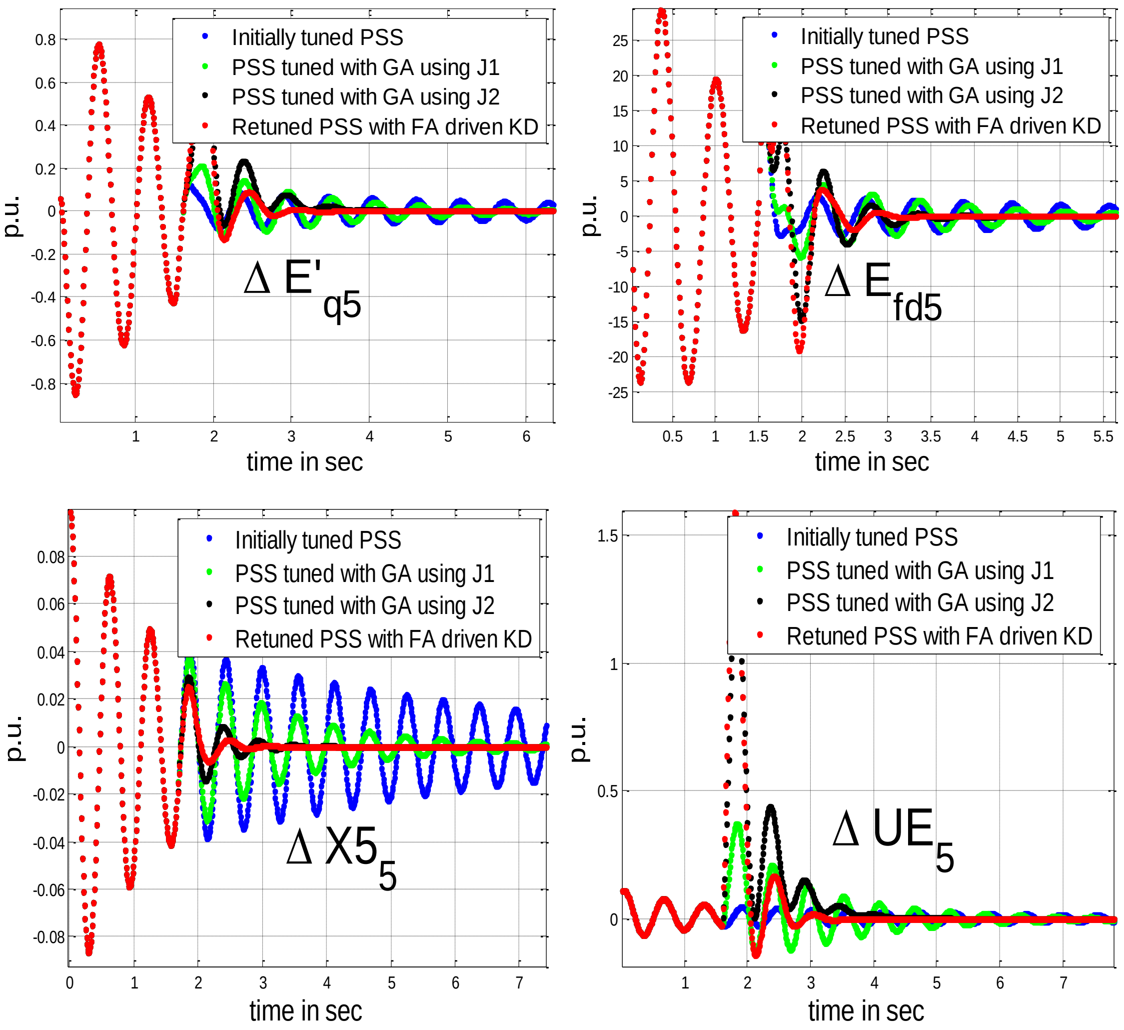


Figure 5.8 Perturbed responses with proposed concept (FA driven KDIM) for Case 5.5 (only PSS)

Table 5.2 Comparison in system responses with Case 5.4 and Case 5.5

System	States	Over-shoot	Settling Time	Eigenvalues
CASE 5.4 Initially tuned PSS as load change (Area 3)	$\Delta\omega_3$	-0.065	5.50	-7.7106 +11.4663i
	$\Delta\delta_3$	-02.90	6.50	-7.7106 -11.4663i
	$\Delta E'_{q3}$	-01.00	7.20	-0.8464 + 5.4641i
	ΔE_{fd3}	-20.00	6.50	-0.8464 - 5.4641i
	$\Delta X5_3$	-00.06	5.80	-0.1264
	ΔUE_3	00.10	4.50	-0.3599
CASE 5.4 Retuned PSS with FA driven KDIM as load change (Area 3)	$\Delta\omega_3$	-00.05	2.90	-5.6844 + 9.8392i
	$\Delta\delta_3$	-00.08	3.10	-5.6844 - 9.8392i
	$\Delta E'_{q3}$	-01.40	3.20	-0.1266
	ΔE_{fd3}	-20.00	3.40	-3.3946 + 6.0509i
	$\Delta X5_3$	-00.05	2.90	-3.3946 - 6.0509i
	ΔUE_3	00.28	3.40	-10.4385

CASE 5.5 Initially Tuned PSS as load change (Area 5)	$\Delta\omega_5$	00.04	15.00	-8.3433 +19.2333i
	$\Delta\delta_5$	01.0	15.00	-8.3433 -19.2333i
	$\Delta E'_{q5}$	00.10	12.0	-0.1857 +11.1465i
	ΔE_{fd5}	10.00	12.0	-0.1857 -11.1465i
	$\Delta X5_5$	00.04	16.0	-0.1434
	ΔUE_5	00.08	10.0	-0.3553
CASE 5.5 PSS Tuned with genetic algorithm with J1 cost function (Area 5)	$\Delta\omega_5$	0.038	6.50	-7.8740 +19.0033i
	$\Delta\delta_5$	0.95	6.80	-7.8740 -19.0033i
	$\Delta E'_{q5}$	0.21	6.30	-0.6358 +11.2192i
	ΔE_{fd5}	9.8	6.40	-0.6358 -11.2192i
	$\Delta X5_5$	0.04	6.70	-2.1001
	ΔUE_5	0.38	6.30	-0.1428
CASE 5.5 PSS tuned with genetic algorithm with J2 cost function (Area 5)	$\Delta\omega_5$	0.03	3.50	-6.1854 +18.3228i
	$\Delta\delta_5$	0.45	3.40	-6.1854 -18.3228i
	$\Delta E'_{q5}$	0.65	3.30	-2.2960 +11.5101i
	ΔE_{fd5}	11.1	3.40	-2.2960 -11.5101i
	$\Delta X5_5$	0.03	3.60	-1.7575
	ΔUE_5	1.3	4.10	-0.1427
CASE 5.5 Retuned PSS with FA driven KDIM as load change (Area 5)	$\Delta\omega_5$	00.02	2.50	-4.8090 +18.9693i
	$\Delta\delta_5$	00.35	2.50	-4.8090 -18.9693i
	$\Delta E'_{q5}$	00.75	2.90	-3.3040 +10.0833i
	ΔE_{fd5}	15.00	2.90	-3.3040 -10.0833i
	$\Delta X5_5$	0.021	2.60	-3.9647
	ΔUE_5	01.35	3.20	-0.1424

Table 5.3 Parameters of PSS with FA driven knowledge domain in Six Area system at different operating conditions with Case 5.4 and Case 5.5

	For L3(0)	**For L3(1)**	**For L3(2)**
Case 5.4	T113=0.3558 T213=1.5332 Kc31=5.0766 ITAE=60.1809	T113=0.1306 T213=0.0803 Kc31=8.3636 ITAE=77.0943	T113=0.0392 T213=0.0870 Kc31=22.6523 ITAE=78.5973
Case 5.5 With FA Driven KD	**For L5(0)**	**For L5(1)**	**For L5(2)**
	T115=0.9163 T215=0.3190 Kc51=11.8101 ITAE=75.5868	T115=0.1453 T215=2.7909 Kc51=15.2704 ITAE=139.5359	T115=0.1453 T215=2.7909 Kc51=15.2704 ITAE=139.535
PSS tuned with GA (Cost=J1)	T115=0.6000; T215=0.48447; Kc51=5.2353; Cost J1= 0.3572		
PSS tuned with GA (Cost=J2)	T115=0.77098; T215=0.60078; Kc51=18.275; Cost J2= 95.5089;		

Perturbed responses of all states are compared with the response when controller settings are unchanged. The proposed concept demonstrates that as system operating condition changes with time, retuning of respective control parameters from the knowledge domain not only improves oscillation damping but performs better. Figures 5.7 and 5.8 show the perturbation response of system state variables for cases 5.4 and 5.5 respectively. The effectiveness of the FA driven knowledge domain concept has been compared with initially tuned PSS along with PSS tuned by GA using two different objective functions as given by Equation (5.1) and (5.2). Results reflect that overshoot/ undershoot and settling time of state variables are greatly reduced by proposed concept for tuning of controllers. A CPU effort for the control parameter upgrading from one point to another point is 0.4299 sec (Windows 7 Ultimate, processor-Intel core-i3 with 4GB RAM and MATLAB 2009b version).

PSO Driven Knowledge Domain States Mapping Concept - PSS Design

Sample six area test system has been considered with UPFC connected between area 2 and area 3 and PSS to all the generators as shown in Figure 5.2. Time constants (T1 and T2) of lead-lag compensation block and gain (Kc) are used as the control parameters for PSS and amplitude modulation ratio (Δm_e and Δm_b) and phase angles ($\Delta\delta_e$ and $\Delta\delta_b$) for UPFC. Particle swarm optimization technique is used to tune these control parameters by minimizing cost function J (Equation 5.2). Two cases have been taken to study the behavior of controllers at different operating conditions. Table 5.4 shows the comparison between system responses in terms of overshoot/undershoot and settling time for tuning of controller with PSO driven knowledge domain over conventional phase compensation method. First two part of the table shows the system response when load L1 (susceptance (B6)=2.9 with conductance (G6)=1.8) is changes at initial time (t_1=0 sec) for area 6 and last two part of the table shows the system response when 10% increase in load after t_2 second (t_2=1sec) (Case 5.6).

Table 5.4 Comparison in system response with and without PSO driven KDIM for Six Area system with Case 5.6

System	**State**	**Over-shoot**	**Settling time**	**Eigenvalues 1.0e+03***
System without PSO (load change L1 at initial time)	$\Delta\omega_6$	00.10	06.80	-0.0127
	$\Delta\delta_6$	03.40	09.50	-0.0020 + 0.0118i
	$\Delta E'_{q6}$	-00.98	09.20	-0.0020 - 0.0118i
	ΔE_{fd6}	-17.00	09.50	-0.0005 + 0.0030i
	$\Delta X5_6$	00.10	06.80	-0.0005 - 0.0030i
	ΔUE_6	01.25	07.00	-0.0003
System with PSO driven KDIM (load change L1 at initial time)	$\Delta\omega_6$	00.10	03.50	-0.0013 + 0.0098i
	$\Delta\delta_6$	03.20	03.50	-0.0013 - 0.0098i
	$\Delta E'_{q6}$	-00.40	03.00	-0.0004
	ΔE_{fd6}	04.00	02.80	-0.0024
	$\Delta X5_6$	00.10	03.40	-0.0048 + 0.0044i
	ΔUE_6	-00.70	02.90	-0.0048 - 0.0044i
System without PSO (load increased 10 % at time 1 sec)	$\Delta\omega_6$	-00.12	09.40	-0.0133
	$\Delta\delta_6$	08.20	13.00	-0.0004 + 0.0030i
	$\Delta E'_{q6}$	-02.25	13.50	-0.0004 - 0.0030i
	ΔE_{fd6}	-26.00	12.50	-0.0003
	$\Delta X5_6$	00.15	14.00	-2.5922
	ΔUE_6	-02.00	13.20	-1.2860
System with PSO driven KDIM (load increased 10 % at time 1 sec)	$\Delta\omega_6$	00.10	03.20	-0.0017 + 0.0115i
	$\Delta\delta_6$	03.15	03.90	-0.0017 - 0.0115i
	$\Delta E'_{q6}$	-00.42	04.50	-0.0072 + 0.0037i
	ΔE_{fd6}	04.40	03.50	-0.0072 - 0.0037i
	$\Delta X5_6$	00.10	03.90	-0.0004
	ΔUE_6	00.10	03.40	-0.0026

Table 5.5 Initial control parameters of PSS and UPFC for Case 5.6

Parameters of UPFC	m_e =0.85, δ_e =0.03, m_b =0.85, δ_b =0.3		
Parameters of PSS	Generator G1	T11=2.5200	T21=0.1765
	Generator G2	T12=1.7773	T22=0.6594
	Generator G3	T13=2.9999	T23=2.6629
	Generator G4	T14=0.0824	T24=0.0823
	Generator G5	T15=0.0353	T25=0.6471
	Generator G6	T16=0.0039	T26=0.0863

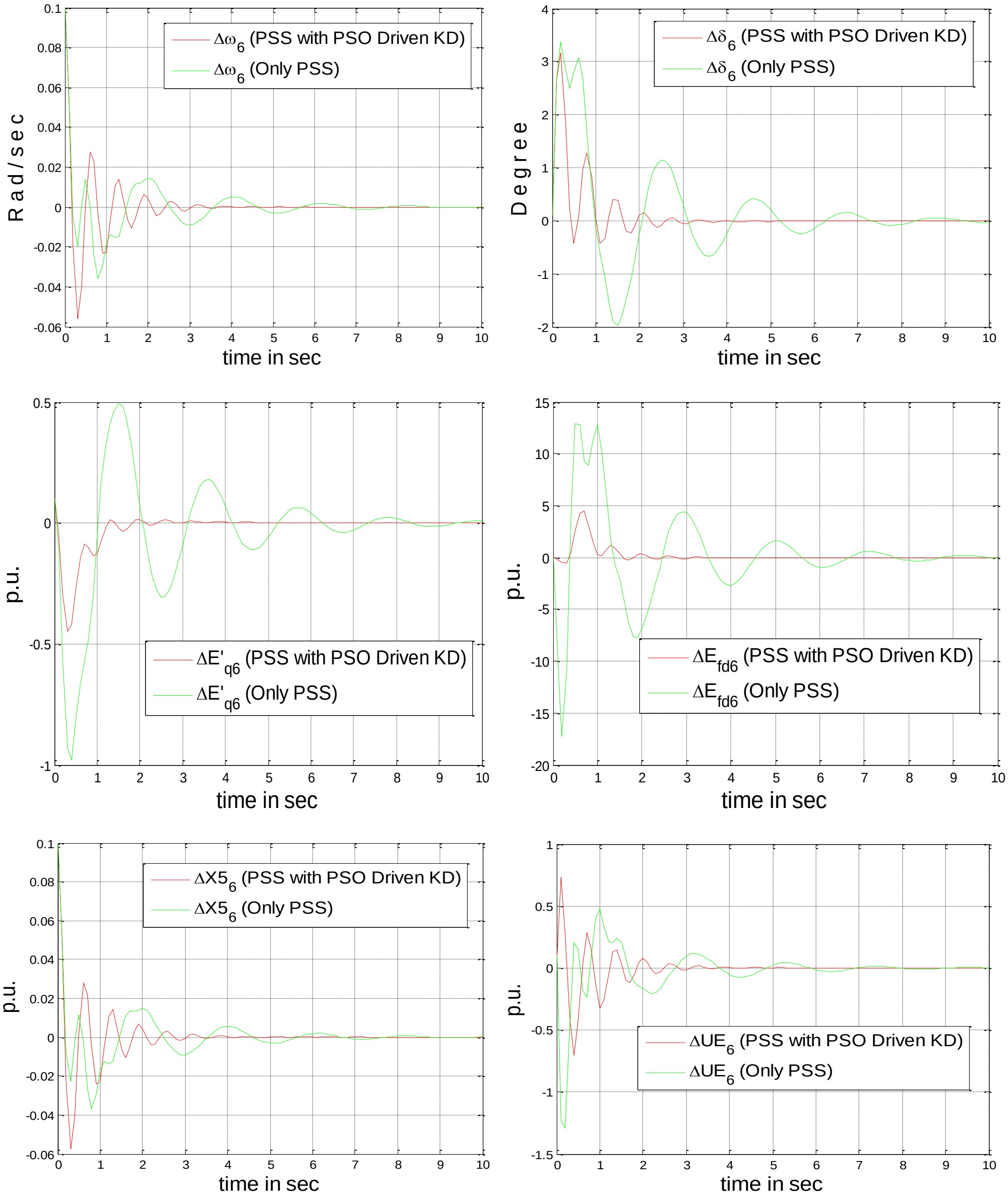


Figure 5.9 Perturbation response for Area 6 of system state without PSO and with PSO driven knowledge domain at time t_1 (t_1=0 sec) (Case 5.6)

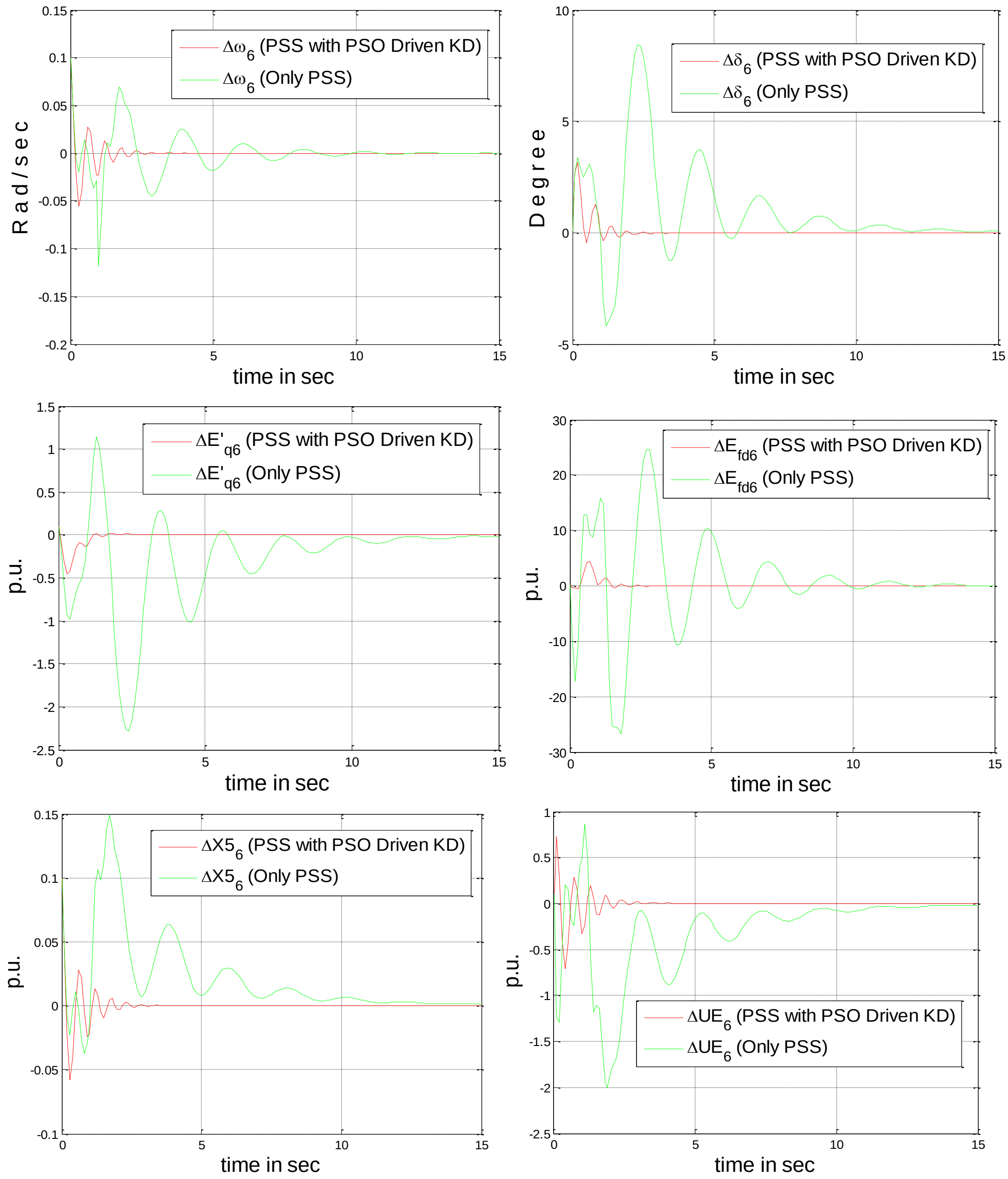


Figure 5.10 Perturbation responses for Area 6 of system states with PSO driven knowledge domain as load increased by 10 % after time t_2 (1 second) (Case 5.6)

The results demonstrate the effectiveness of PSS tuning with PSO driven knowledge domain states mapping concept for dynamic system operating condition by enhancing damping in the system, and therefore enhances system stability. Figures 5.9 and 5.10 show the system state variables perturbation response at different changing load condition. The results show that overshoot/ undershoot and settling time of the system state variables are greatly reduced by applying the proposed concept for tuning of controllers. In these figures “Only PSS” term is used for the tuning of PSS parameters with conventional lag-lead phase compensation method.

Figure 5.2 shows the initial load and correspondingly tuned PSS parameters (such as Kc, T1 and T2). Now 10% additional change is being offered at the same location which can be reflected as additional oscillation by classical PSS, i.e., without any PSS parameter up-gradation. However, with 10% associated change in PSS with PSO driven knowledge domain these oscillations are quickly damped. The results demonstrate that tuning of PSS should be done as dynamical changes are observed at regular intervals in power system failing which these oscillations might be injected into grid and may hamper the other PSS working at different location, and thus may enter into the low-frequency oscillation over period of time. Hence dynamical tuning has been proposed in knowledge domain framework keeping in mind the smart generation control with intelligent switching for associated operating point shift. In the end, it can be commented that precise tuning of PSS alone for various operating conditions can be synthesized with new control parameters driven by intelligent concept for smooth functioning of entire power system with almost least excursions at various points of power system. This will help in controller improved performance and extended life of generators, loads and network as whole.

GSA Driven Knowledge Domain States Mapping Concept - PSS Design

Gravitational Search Algorithm (GSA) has been used to develop knowledge domain structure for sample six area test system shown in Figure 5.6. Case study has been developed by varying the loading condition in area 3 and PSS retuning has been done with the help of GSA driven knowledge domain inference mechanism concept to understand the behavior of the system.

Case 5.7: Load L3(1) at time t_1 =0 sec is 1.6 (p.u.) and at time t_2=2.5 sec load L3(2) reduced to 0.8 (p.u.).

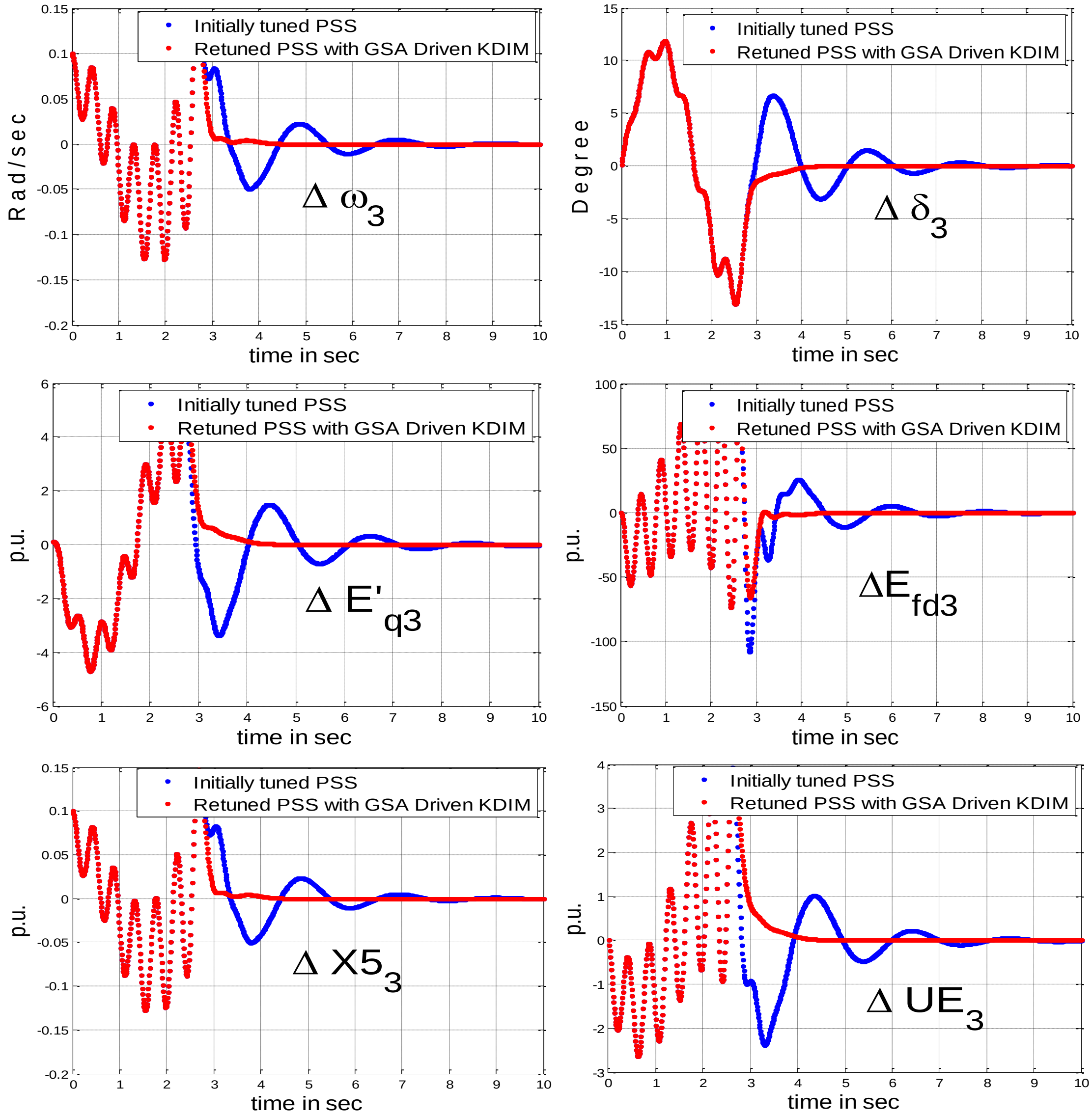


Figure 5.11 Perturbation responses for Area 3 of system states with GSA driven knowledge domain as load reduced after time t_2 (2.5 seconds) (Case 5.7)

Table 5.6 Comparison in system response for Area 3 with and without GSA driven knowledge domain concept for Six Area system – Case 5.7

System	States	Over-shoot	Settling Time	Eigenvalues
CASE 5.7 Initially tuned PSS as load change (Area 3)	$\Delta\omega_3$	00.15	8.10	-3.0591 +14.3573i
	$\Delta\delta_3$	06.50	8.20	-3.0591 -14.3573i
	$\Delta E'_{q3}$	05.00	8.10	-12.9564
	ΔE_{fd3}	50.00	8.30	-0.7330 + 3.0407i
	$\Delta X5_3$	00.15	8.20	-0.7330 - 3.0407i

	ΔUE_3	04.00	9.10	-0.1227
CASE 5.7 Retuned PSS with GSA Driven KD as load change (Area 3)	$\Delta\omega_3$	00.15	4.10	-5.3379 +11.8651i
	$\Delta\delta_3$	04.50	3.90	-5.3379 -11.8651i
	$\Delta E'_{q3}$	05.00	4.00	-2.8189 + 4.9954i
	ΔE_{fd3}	45.50	3.50	-2.8189 - 4.9954i
	$\Delta X5_3$	00.15	4.20	-2.7471
	ΔUE_3	03.80	4.20	-0.1245

Table 5.7 PSS parameters tuned with GSA driven KDIM at different operating conditions - Case 5.7

Loading in Area 3	**Tuning of PSS for Generator**	**Time Constant (T1)**	**Time Constant (T2)**	**Gain (Kc)**	**ITAE**
L(0)=1.0 p.u.	G3	0.4398	1.2984	5.0000	61.8120
L(1)=1.6 p.u.	G3	0.5413	1.3141	5.0001	414.4180
L(2)=0.8 p.u.	G3	0.8310	0.5134	6.5420	66.2303

Figure 5.11 shows dynamic behavior of all the state variables response of area 3 for case 5.7. GSA driven knowledge domain states mapping concept retunes parameters of PSS as the system operating conditions changes and increases the damping in system by quick modulation of power. Table 5.6 shows the settling time, peak overshoot/undershoot and eigenvalues of the system and Table 5.7 gives the parameters of PSS at different operating conditions along with the values of ITAE performance indices.

Tuning of PSS Controller with all the three Optimization Techniques with KD States Mapping Concept

Previous case studies demonstrate the effectiveness of proposed knowledge domain states mapping concept where knowledge domain structure has been developed by all the three optimization techniques separately. However one case study has been developed and comparison has been made to find out which intelligent optimization techniques give the best optimal tuning for PSS controllers in terms of damping and overshoot/undershoot of all the states variables of the complete test system (refer Figure 5.6).

Case Study 5.8: Initial load PLI(1)=1.5; at time t_1=0 sec and change in load PLI(2)=0.7; at time t_2=1.5 sec with controller switching delay=0.1 sec. L3=G3+jB3; where G3= 1.6615; and B3= 1.9029 then L3(1)=L3*PLI(1); L3(2)=L3*PLI(2).

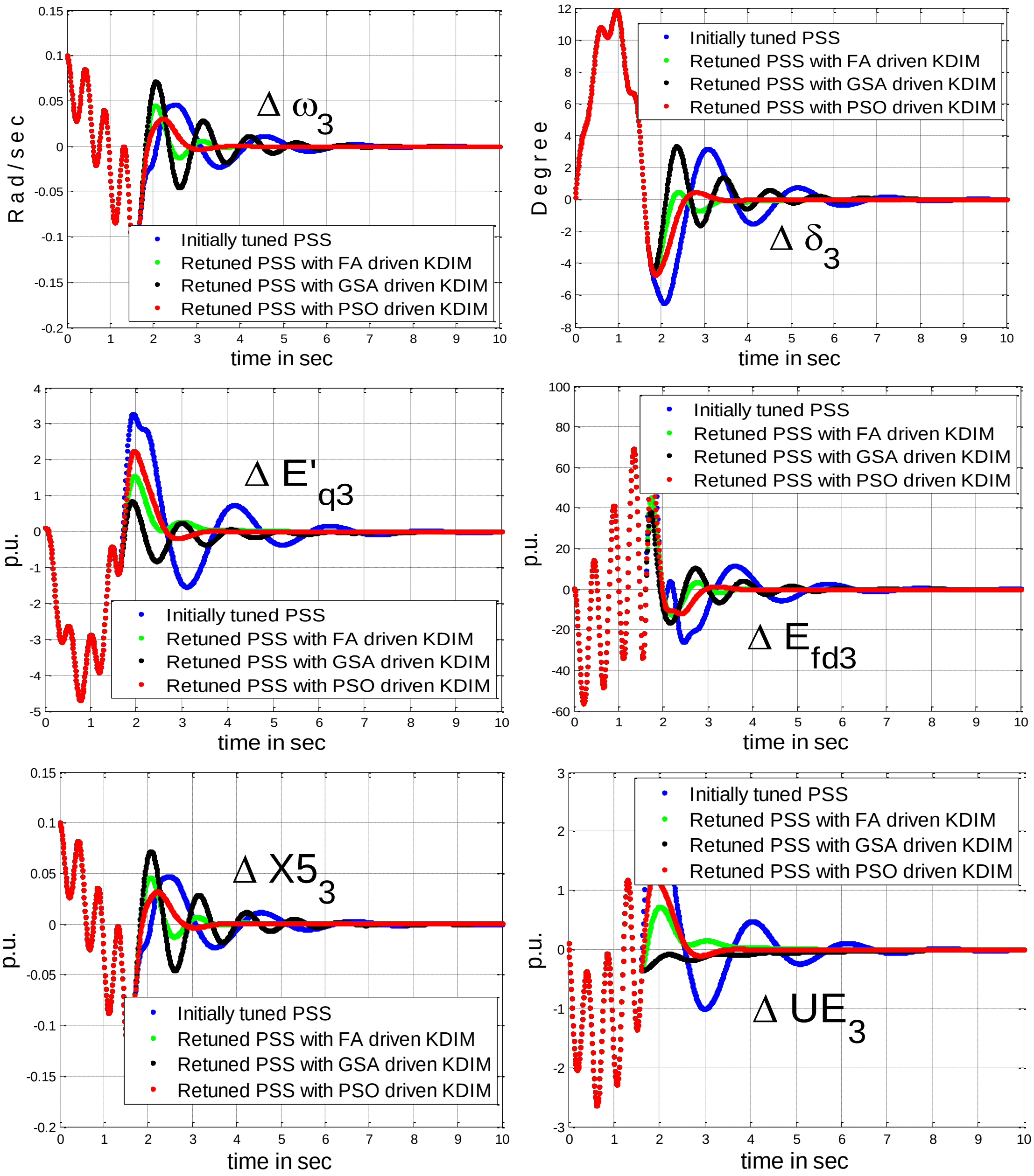


Figure 5.12 States response with all the three optimization techniques driven KD states mapping concept for Six Area System (Case 5.8)

Table 5.8 Eigenvalues for all the three optimization technique based controller design - Case 5.8

Initially Tuned Controller	**FA Driven Controller**	**GSA Driven Controller**	**PSO Driven Controller**
Eigenvalues	Eigenvalues	Eigenvalues	Eigenvalues
-3.4546 +14.1472i	-6.5764 +11.8208i	-7.7068 +12.4160i	-5.0168 +12.3296i
-3.4546 -14.1472i	-6.5764 -11.8208i	-7.7068 -12.4160i	-5.0168 -12.3296i
-12.2309	-1.9861 + 5.9446i	-0.8563 + 5.8190i	-2.4515 + 3.7437i
-0.6965 + 3.0175i	-1.9861 - 5.9446i	-0.8563 - 5.8190i	-2.4515 - 3.7437i
-0.6965 - 3.0175i	-0.1261	-0.1268	-4.2906
-0.1227	-1.2361	-0.4519	-0.1241

Table 5.9 Settling time and overshoot/undershoot for all the three optimization techniques based controller design - Case 5.8

	States	**I.T.C.S.**	**F.A.D.C.S.**	**G.S.A.D.C.S.**	**P.S.O.D.C.S.**
(S.T.)	$\Delta\omega_3$	7.1	3.5	5.5	3.1
	$\Delta\delta_3$	6.9	3.9	5.9	3.2
	$\Delta E'_{q3}$	6.9	3.5	4.9	3.2
	ΔE_{fd3}	6.5	3.5	5.0	2.9
	$\Delta X5_3$	6.1	3.2	6.0	2.9
	ΔUE_3	6.8	3.5	4.0	3.2
(F.P.O.S.)	$\Delta\omega_3$	0.049	0.019	0.065	0.035
	$\Delta\delta_3$	-6.6	-4.5	-5.0	-5.0
	$\Delta E'_{q3}$	3.4	1.5	0.9	2.1
	ΔE_{fd3}	8.0	45	40	60
	$\Delta X5_3$	0.05	0.05	0.06	0.03
	ΔUE_3	2.3	0.9	-0.3	1.2

Here, I.T.C.S.=Initially Tuned Controller Settling; F.A.D.C.S.=Firefly Algorithm Driven Controller Settling; G.S.A.D.C.S.=Gravitational Search Algorithm Driven Controller Settling; P.S.O.D.C.S.=Particle Swarm Optimization Driven Controller Settling; S.T=Settling Time; F.P.O.S=First Peak Overshoot.

Table 5.10 PSS controller parameters with all the three optimization techniques - Case 5.8

	T1(Time Constant)	**T2(Time Constant)**	**Kc(Gain)**
(I.T.C.S) Load L3(1)	T31=1.119;	T32=0.2919;	Kc3=7.3787;
(F.A.D.C.S.) Load L3(2)	T31=0.3814;	T32=0.7953;	Kc3=16.5747;
(G.S.A.D.C.S.) Load L3(2)	T31=0.1727;	T32=2.1051;	Kc3=12.3557;
(P.S.O.D.C.S.) Load L3(2)	T31=0.9889;	T31=0.4714;	Kc3=6.7255;

Figure 5.12 represents states response with all the three optimization techniques driven KD states mapping concept for six area system. From figure, it is clear that among all the three optimization techniques, particles swarm optimization technique gives the best results in terms of settling time and overshoot/undershoot. Table 5.8 shows eigenvalues for all the three controllers along with initially tuned controller whereas Table 5.9 and 5.10 gives the settling time, peak overshoot and PSS controller parameters respectively.

Sample Ten Area Fifty Machine Test System:

A Sample Ten Area Fifty Machine test system is developed (refer Figure 5.13) based on model given in chapter 3. Control parameter up-gradation based on knowledge domain states mapping concept is used to retune control parameters of PSS connected in the system at different perturbation. In each area, all the generators and their PSS are of different ratings. Time constants (T1 and T2) of lead-lag phase compensation block and gain (Kc) of PSS are tuned by minimizing ITAE as an optimization problem. One case study has been developed by changing the load demand in area 2.

Case 5.9- Load L2(1) at time t_1 and L2(2) at time t_2,

L2(1)=G2(1)+jB2(1) and L2(2)=G2(2)+jB2(2); G2(1)= 5.5660, B2(1)=6.2763, G2(2)=6.6792, B2(2)= 7.5316,

i.e. L2(2)=1.20*L2(1) and t_1=0 sec and t_2=1.5 sec with controller switching time delay (Tsd) =0.1 sec.

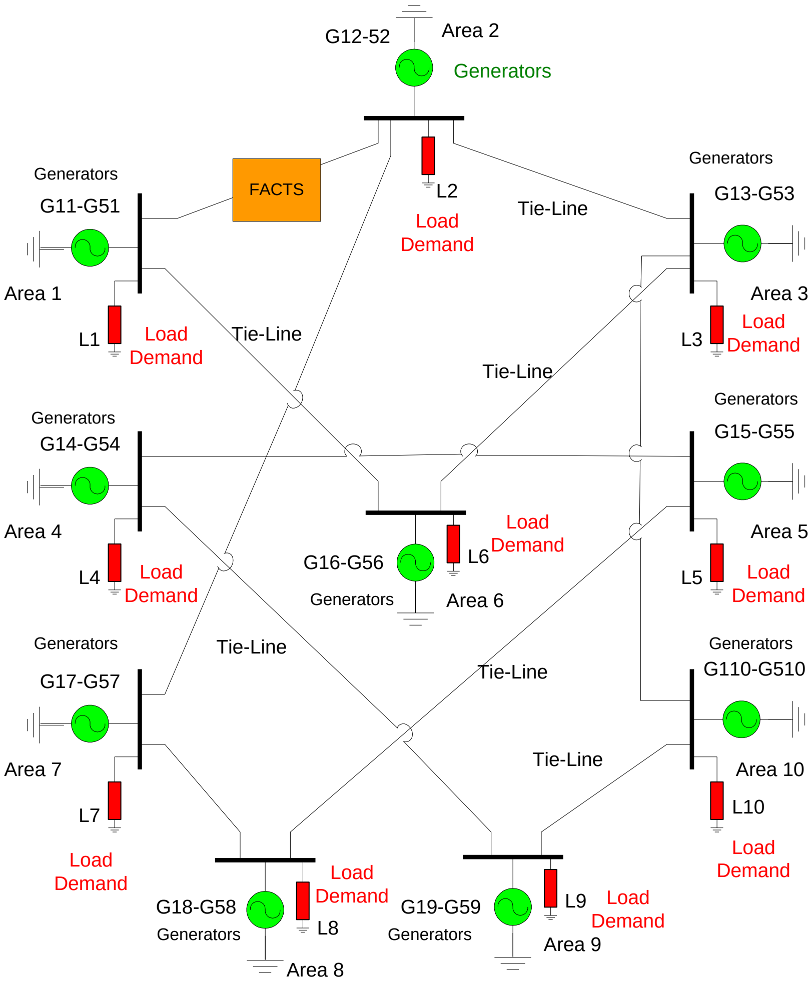


Figure 5.13 Ten Area Fifty Machines power system - PSS with each generator

Simulation has been carried out for the above case study and perturbation response of states variables (angular speed (Δω) and phase angles (Δδ)) are shown in Figures 5.14 and 5.15. Figures show effectiveness of the concept (Knowledge Domain States Mapping) as system operating condition changes. Simulation results also compare the performance of different optimization techniques for development of knowledge domain. Particle swarm optimization technique shows the better performance as compared to other two techniques (GSA and FA) used, although it is the oldest one. Responses of the states shown in Figures 5.14 and 5.15 show the discontinuity at time 1.5 sec which is nothing but the variation of states when system loading is changed (increase by 20 %) and correspondingly controller parameters shift their values to the new one. All state variables follow the similar behavior.

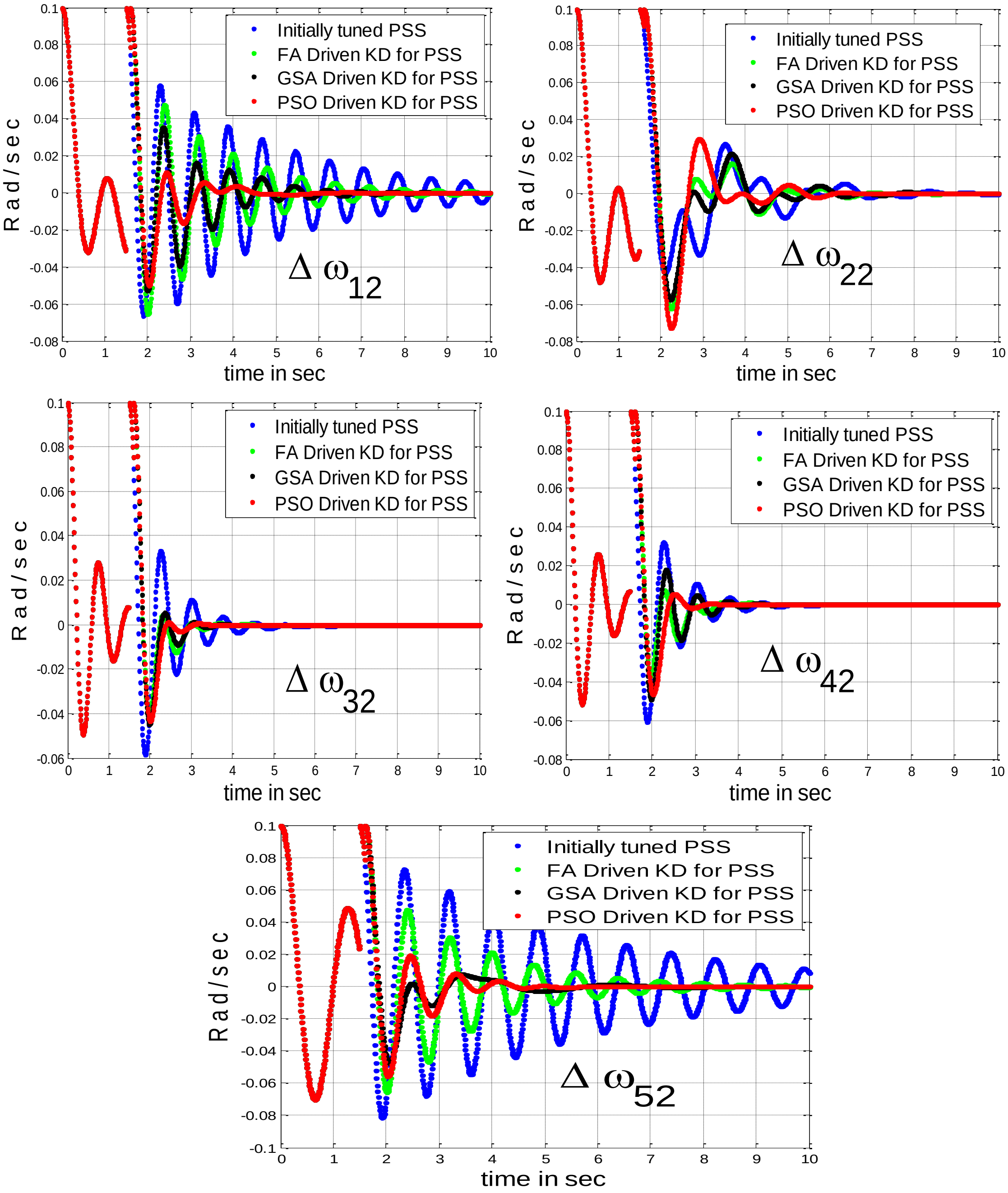
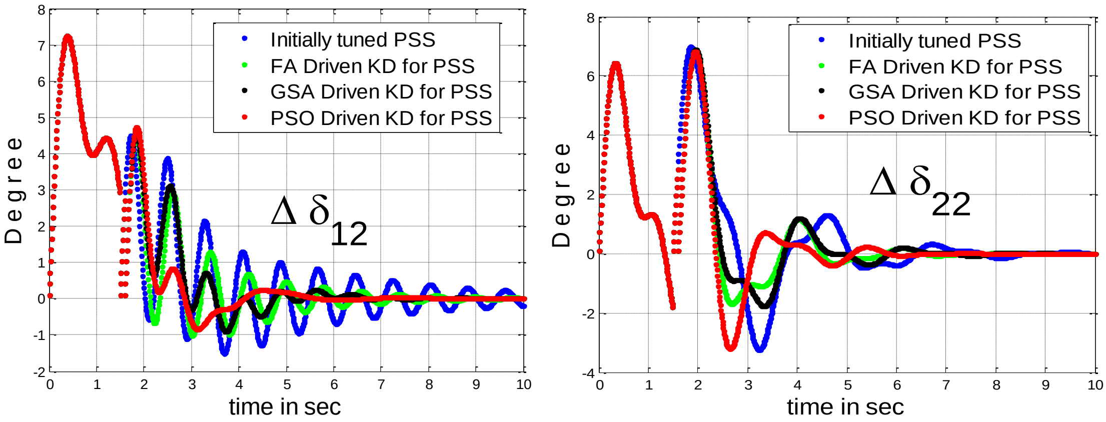


Figure 5.14 Angular speed deviation for all the generators connected in Area 2 (Case 5.9)



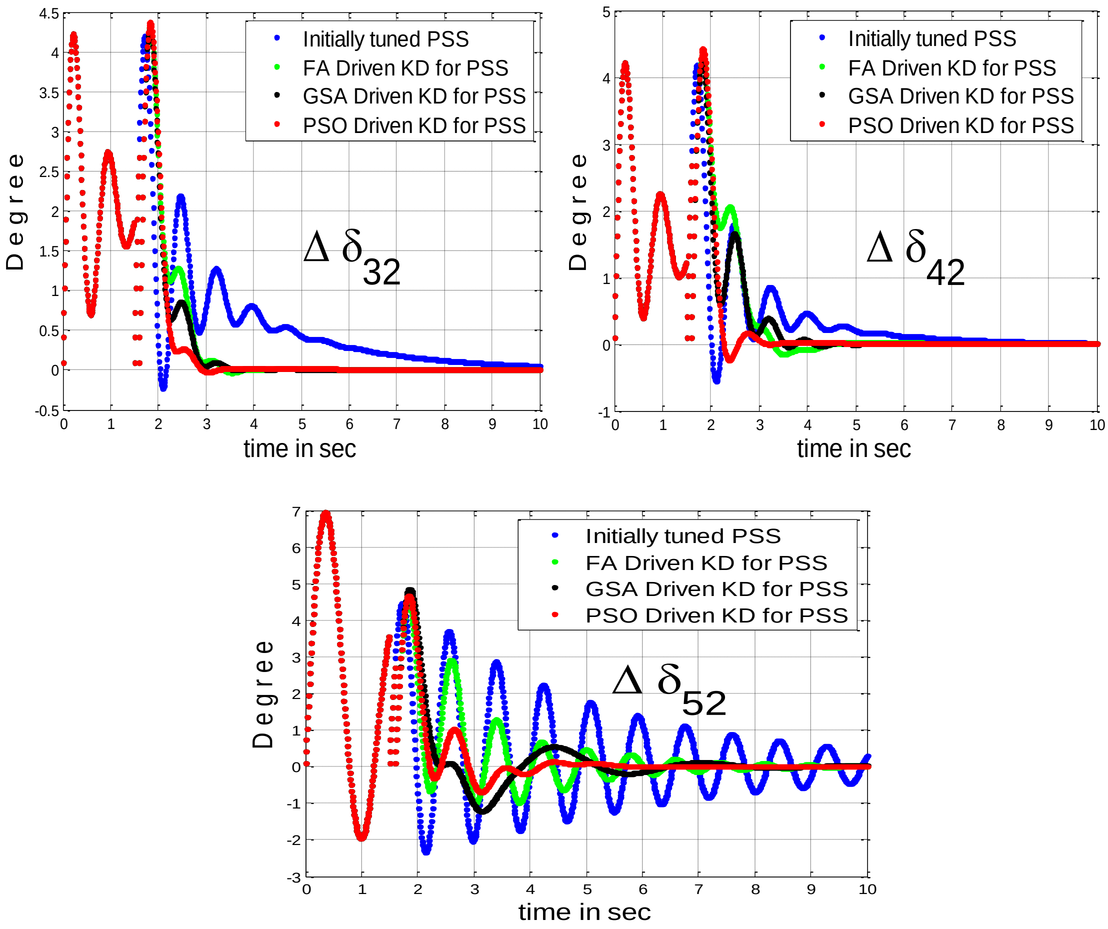


Figure 5.15 Phase angle deviation for all the generators in Area 2 (Case 5.9)

Table 5.11 Comparison of system response with all the three optimization techniques for Ten Area Fifty Machine system (Area 2) - Case 5.9

Case 5.9	**States**	**I.T.C.S.**	**F.A.D.C.S.**	**G.S.A.D.C.S.**	**P.S.O.D.C.S.**
(S.T.)	$\Delta\omega_{12}$	15.00	08.50	07.00	04.40
	$\Delta\omega_{22}$	06.80	06.50	06.50	05.20
	$\Delta\omega_{32}$	05.10	03.10	03.20	02.90
	$\Delta\omega_{42}$	04.50	03.80	03.90	02.80
	$\Delta\omega_{52}$	20.00	08.50	04.50	04.10
	$\Delta\delta_{12}$	13.00	08.50	06.50	05.20
	$\Delta\delta_{22}$	08.50	06.10	06.50	05.80
	$\Delta\delta_{32}$	08.90	03.50	03.50	02.90
	$\Delta\delta_{42}$	06.50	04.20	04.10	03.10
	$\Delta\delta_{52}$	15.00	07.10	06.50	04.20
(F.P.O.S.)	$\Delta\omega_{12}$	-00.065	-00.064	-00.051	-00.049
	$\Delta\omega_{22}$	-00.042	-00.061	-00.058	-00.071
	$\Delta\omega_{32}$	-00.059	-00.042	-00.043	-00.042
	$\Delta\omega_{42}$	-00.060	-00.040	-00.050	-00.048
	$\Delta\omega_{52}$	-00.08	-00.066	-00.051	-00.055
	$\Delta\delta_{12}$	04.50	04.500	04.50	04.60
	$\Delta\delta_{22}$	07.00	06.90	06.90	06.90
	$\Delta\delta_{32}$	04.30	04.40	04.40	04.40
	$\Delta\delta_{42}$	04.30	04.50	04.50	04.50
	$\Delta\delta_{52}$	04.50	04.60	04.70	04.60

Table 5.12 Parameters of PSS tuned with all the three optimization techniques driven knowledge structure in Area 2 at different operating conditions - Case 5.9

	T1(Time Constant)	**T2(Time Constant)**	**Kc(Gain)**
(I.T.C.S) Load L2(1) (G1+jB1)	T11=1.6955; T12=2.5632; T13=1.7500; T14=0.8628; T15=1.1166;	T21=0.1976; T22=0.3466; T23=2.3798; T24=2.0151; T25=2.0507;	Kc1=08.8890; Kc2=18.8107; Kc3=14.3051; Kc4=14.8146; Kc5=14.6821;
(F.A.D.C.S.) Load L2(2) (G2+jB2)	T11=1.2941; T12=1.7653; T13=0.2647; T14=0.8692; T15=1.2941;	T21=0.1173; T22=0.3014; T23=0.1145; T24=0.1738; T25=0.1173;	Kc1=07.0869; Kc2=14.5355; Kc3=21.6663; Kc4=10.0311; Kc5=07.0869;
(G.S.A.D.C.S.) Load L2(2) (G2+jB2)	T11=0.9101; T12=2.3526; T13=0.2088; T14=0.5198; T15=0.1454;	T21=0.1019; T22=0.3238; T23=0.0898; T24=0.2134; T25=0.0100;	Kc1=15.8720; Kc2=13.3576; Kc3=19.1335; Kc4=11.7809; Kc5=14.6566;
(P.S.O.D.C.S.) Load L2(2) (G2+jB2)	T11=0.6596; T11=0.6831; T11=0.4950; T11=0.3185; T11=0.5067;	T21=0.0245; T21=0.2480; T21=0.0598; T21=0.0363; T21=0.0245;	Kc1=06.4118; Kc2=22.9608; Kc3=05.3137; Kc4=05.2353; Kc5=07.0392;

Table 5.13 Eigenvalues of system of Area 2 for all the three optimization techniques with Case 5.9

Initially Tuned Controller	**FA Driven Controller**	**GSA Driven Controller**	**PSO Driven Controller**
Eigenvalues	Eigenvalues	Eigenvalues	Eigenvalues
-0.3232+7.9459i	-9.9361	-11.65	-41.0085
-0.3232-7.9459i	-0.5704+7.9048i	-00.80+08.23i	-1.6981+7.495i
-7.3145	-0.5704-7.9048i	-00.80-08.23i	-1.6981-7.495i
-1.1934+1.3913i	-1.3680+1.5276i	-00.93+01.77i	-0.8621+2.214i
-1.1934-1.3913i	-1.3680-1.5276i	-00.93-01.77i	-0.8621-2.214i
-0.3056	-0.3049	-00.29	-0.2802
-0.5720+6.4770i	-0.8251+5.9693i	-00.74+06.10i	-5.4520
-0.5720-6.4770i	-0.8251-5.9693i	-00.74-06.10i	-0.9717+5.608i
-5.8321	-5.3073	-05.33	-0.9717-5.608i
-0.6435+2.5684i	-0.8657+3.0566i	-00.82+02.89i	-1.0016+3.491i
-0.6435-2.5684i	-0.8657-3.0566i	-00.82-02.89i	-1.0016-3.491i
-0.3156	-0.3225	-00.32	-0.3271
-12.6555	-15.9960	-16.69	-20.0631
-1.3459+8.3404i	-2.3720+9.2159i	-02.56+08.83i	-3.3873+8.140i
-1.3459-8.3404i	-2.3720-9.2159i	-02.56-8.83i	-3.3873-8.140i
-1.5447	-2.4528+1.7263i	-03.12+1.41i	-3.4008+2.164i
-0.3474	-2.4528-1.7263i	-03.12-14.1i	-3.4008-2.164i
-0.4094	-0.3165	-00.32	-0.3115
-12.4862	-2.0468+9.4586i	-13.95	-28.7885
-1.3850+8.2284i	-2.0468-9.4586i	-01.70+08.87i	-3.2659+7.061i
-1.3850-8.2284i	-0.3102	-01.70-08.87i	-3.2659-7.061i
-1.6546	-1.6775+1.8247i	-02.13+01.23i	-4.5729+1.765i
-0.3547	-1.6775-1.8247i	-02.13-01.23i	-4.5729-1.765i
-0.4593	-15.2233	-00.32	-0.3107
-0.2499+7.4821i	-9.9361	-100.04	-40.9777

-0.2499-7.4821i	-0.5704+7.9048i	-02.02+07.21i	-1.4542+7.423i
-3.1818	-0.5704-7.9048i	-02.02-07.21i	-1.4542-7.423i
-1.5838	-1.3680+1.5276i	-00.62+02.39i	-1.1181+2.109i
-0.3448	-1.3680-1.5276i	-00.62-02.39i	-1.1181-2.109i
-0.4701	-0.3049	-00.27	-0.2866

Table 5.14 Cost function with all the three optimization techniques - Case 5.9

Objective Function (Fx)	Firefly Algorithm	Gravitational Search Algorithm	Particles Swarm Optimization
ITAE (G1)	1.5930	0.7800	0.2860
ITAE (G2)	0.6678	0.7587	0.6381
ITAE (G3)	0.1126	0.1064	0.0887
ITAE (G4)	0.1503	0.1920	0.1059
ITAE (G5)	1.5930	0.4471	0.2983
Time to develop KD for each operating point (sec)	61.37914	70.002389	77.827857

Table 5.11 shows the comparison of system responses between all the three optimization techniques in terms of overshoot/undershoot (after change in operating condition at time t_2) and settling time (Overall Response). Controller parameters of PSS (stored in knowledge domain) with different optimization techniques at respected loading are shown in Table 5.12. When actual loading condition approaches very near to initially stored one, control parameter up-gradation takes place by inference mechanism as set of rules framed. Table 5.13 shows eigenvalues for all states variables in area 2 with all the three optimization techniques, and also for initial tuned controller parameter. Table 5.14 shows the objective function minimized by all optimization techniques for specific system operating conditions (i.e. at Load L2 (2)). It also shows the time taken by each optimization techniques to develop knowledge domain for different system operating conditions separately. For searching each optimal control parameter in order to develop knowledge domain structure, PSO takes more time as compared to other two optimization techniques. As development of the knowledge domain is done in offline mode and control activation in dynamical mode with respect to the system operational shift, PSO shows better desired performance as compared to other two optimization techniques. This concept demonstrates as system operating

condition changes with time, retuning (parameter up-gradation) of respective control from knowledge domain will enhance oscillation damping in the system, and therefore, enhance stability of the system.

5.2.1.2 Variation in Transmission Line Length

Tuning of PSS Controller with all the three Optimization Techniques with KD States Mapping Concept

Sample Six Area Test System:

Length of the transmission line has been varied in sample six area system (refer Figure 5.6) for considering another operational shift in the system. By increasing length of transmission line, power carrying capacity of the line decreases which affects the modulation of power flow also. The parametric change of PSS, with the help of knowledge domain states mapping concept, results in reduced power oscillation. The simulation results demonstrate effectiveness of all the three optimization techniques for developing knowledge domain structure and improvement in the system state variables response. Following case study has been carried out by increasing the transmission line length between area 1 and area 3.

Case 5.10: R_13=0.034; X_13=0.6; then: R_13=R_13*ITL1; X_13=X_13*ITL1; Initially ITL1(1)=1.2; then after time 0.1 sec ITL1(2)=1.7.

Here, R_13=Resistance of the transmission line between area 1 and 3. X_13=Reactance of the transmission line between area 1 and area 3. ITL=Increase in Transmission line length.

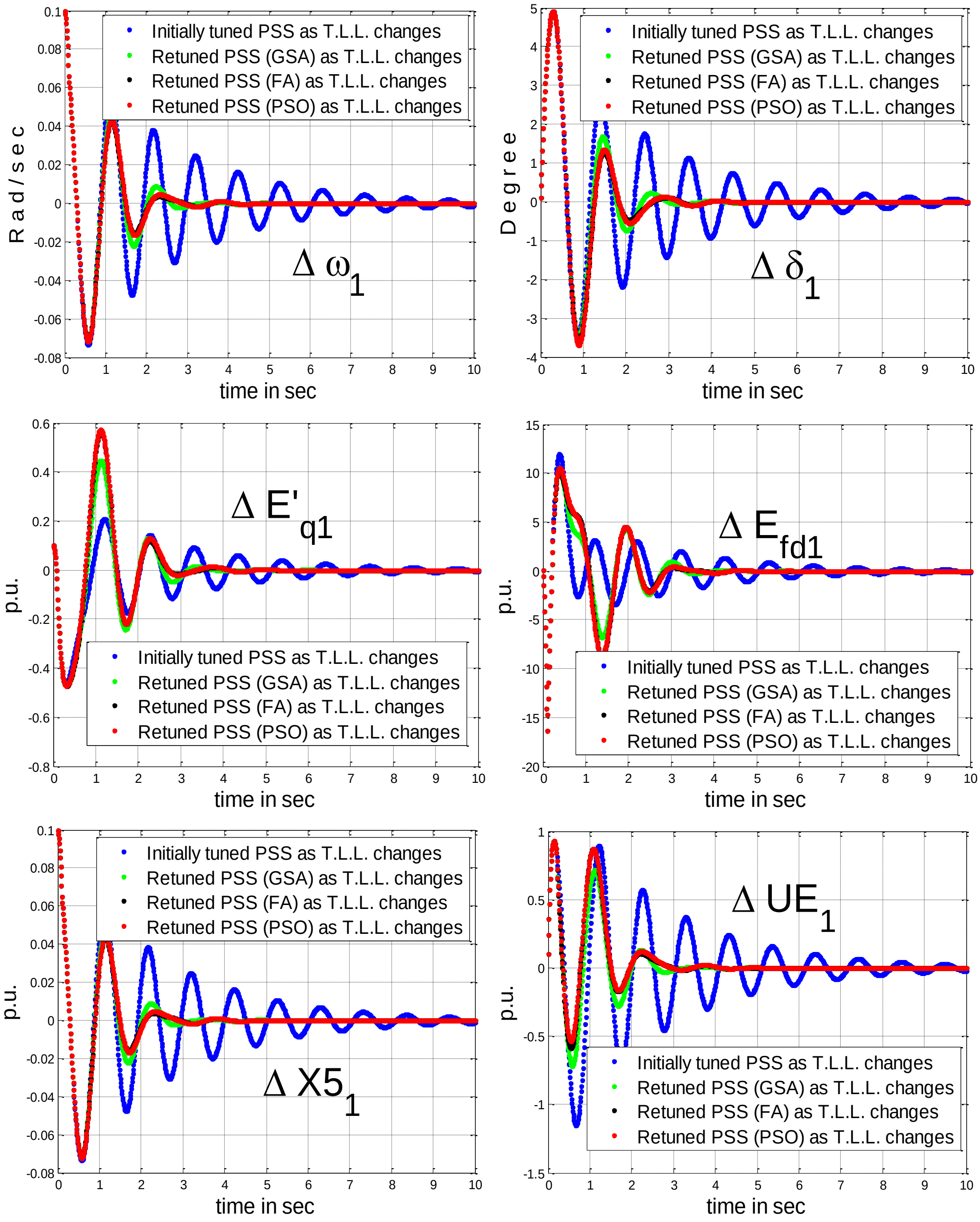


Figure 5.16 Perturbation responses of state variables of Area 1 (Case 5.10)

Table 5.15 Eigenvalues for all the three optimization technique based controller design with variation in transmission line length - Case 5.10

Initially Tuned Controller	**FA Driven Controller**	**GSA Driven Controller**	**PSO Driven Controller**
Eigenvalues	Eigenvalues	Eigenvalues	Eigenvalues
-7.3221	-1.3628 + 6.9862i	-1.3887 + 6.7858i	-1.3628 + 6.9862i
-0.1260	-1.3628 - 6.9862i	-1.3887 - 6.7858i	-1.3628 - 6.9862i
-0.4147 + 6.0859i	-1.3894 + 4.7127i	-1.4005 + 4.9988i	-1.3894 + 4.7127i
-0.4147 - 6.0859i	-1.3894 - 4.7127i	-1.4005 - 4.9988i	-1.3894 - 4.7127i
-2.8247 + 5.6127i	-1.4734	-0.1256	-1.4734
-2.8247 - 5.6127i	-0.1249	-1.9843	-0.1249

Table 5.16 Settling time and overshoot/undershoot for all the three optimization techniques based controller design for area 1 with Case 5.10

	States	**I.T.C.S.**	**F.A.D.C.S.**	**G.S.A.D.C.S.**	**P.S.O.D.C.S.**
(S.T.)	$\Delta\omega_1$	11.5	4.0	3.9	3.9
	$\Delta\delta_1$	12.0	4.2	4.2	4.1
	$\Delta E'_{q1}$	10.5	4.2	4.1	4.1
	ΔE_{fd1}	10.0	3.8	3.7	3.5
	$\Delta X5_1$	11.5	4.1	4.1	4.1
	ΔUE_1	12.0	4.0	4.0	3.9
(F.P.O.S.)	$\Delta\omega_1$	0.06	0.05	0.045	0.044
	$\Delta\delta_1$	2.7	1.8	1.3	1.3
	$\Delta E'_{q1}$	0.21	0.48	0.58	0.58
	ΔE_{fd1}	13.0	11.5	11.6	11.3
	$\Delta X5_1$	0.06	005	0.045	0.044
	ΔUE_1	-1.2	-0.70	-0.60	-0.55

Here, I.T.C.S.=Initially Tuned Controller Settling; F.A.D.C.S.=Firefly Algorithm Driven Controller Settling; G.S.A.D.C.S.=Gravitational Search Algorithm Driven Controller Settling; P.S.O.D.C.S.=Particle Swarm Optimization Driven Controller Settling; S.T=Settling Time; F.P.O.S=First Peak Overshoot.

Table 5.17 PSS controller parameters with all the three optimization techniques for Case 5.10

	T1(Time Constant)	**T2(Time Constant)**	**Kc(Gain)**
(I.T.C.S) Load L3(1)	T11= 0.0100;	T12= 0.1222;	Kc1= 20.3927;
(F.A.D.C.S.) Load L3(2)	T11= 0.7984;	T12= 0.7357;	Kc1= 13.0662;
(G.S.A.D.C.S.) Load L3(2)	T11= 0.2955;	T12= 0.5142;	Kc1= 23.4443;
(P.S.O.D.C.S.) Load L3(2)	T11= 0.8948;	T11= 0.7772;	Kc1= 11.7451;

Figure 5.16 shows states response with all the three optimization techniques driven knowledge domain states mapping concept for sample six area test system when variation of transmission line length has been considered as operational shift in the system. From the figure it is clear that knowledge domain states mapping concept improves the system response as compared to initially tuned controller setting. Performance of knowledge domain structure with all the three optimization techniques have been shown in the Figure 5.16. Among all the three optimization techniques, particles swarm optimization technique gives the best results in terms of settling time and overshoot/undershoot. Table 5.15 shows eigenvalues for all the three controllers along with initially tuned controller, whereas Table 5.16 and 5.17 give settling time, peak overshoot and PSS controller parameters respectively.

Sample Ten Area Fifty Machine Test System:

A Sample Ten Area Fifty Machine test system has been developed (refer Figure 5.13), and variation in transmission line length has been considered as the system operational shift. With increase in length of the transmission line between area 1 and 2, response of state variables changes due to reduction in the Available Transfer Capacity (ATC) of the line which limits the power transfer from one point to another point. With change in controller's parameters with help of knowledge domain states mapping, oscillations can be reduced in system with improved damping. For ten area fifty machine system, the same concept has been demonstrated by generating one case study with increase in length of the transmission line.

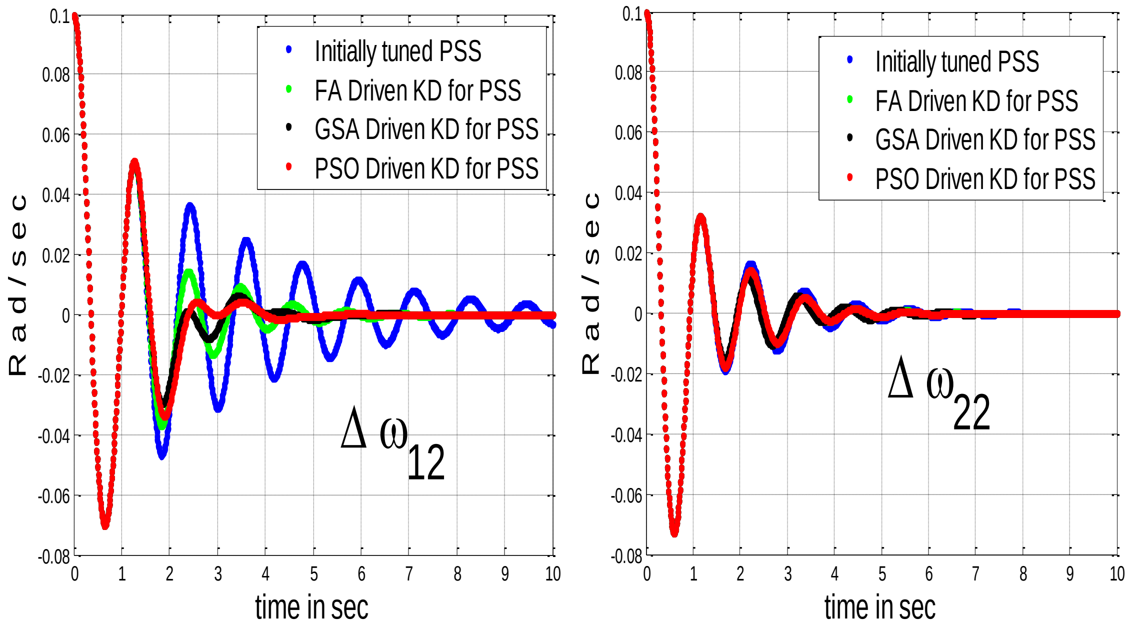
Case 5.11 - R_12= 0.07827; X_12= 0.5194;

R_12(1)=ITL(1)*R_12; X_12(1)=ITL(1)*X_12;

R_12(2)=ITL(2)*R_12; X_12(2)=ITL(2)*X_12;

Initially at time $t_1=0$ sec; ITL(1)=1.0 and at time $t_2=1.0$ sec, ITL(2)=1.4; where ITL=Increase in T.L. Here, R_12=Resistance of transmission line between area 1 and 2, X_12=Reactance of the transmission line between area 1 and 2, and ITL=increase in transmission line length.

Simulation has been carried out for above case study and perturbation response of states variables (angular speed (Δω) and phase angles (Δδ)) are shown in Figures 5.17 and 5.18. All other state variables follow the similar behavior. The response of all these state variables shows the best features of knowledge domain states mapping concept with changing network conditions. Simulation results also compare performance of different optimization techniques for the development of knowledge domain. Here again well-known PSO optimization techniques prove to be the best one among all the three optimization technique used in this research work.



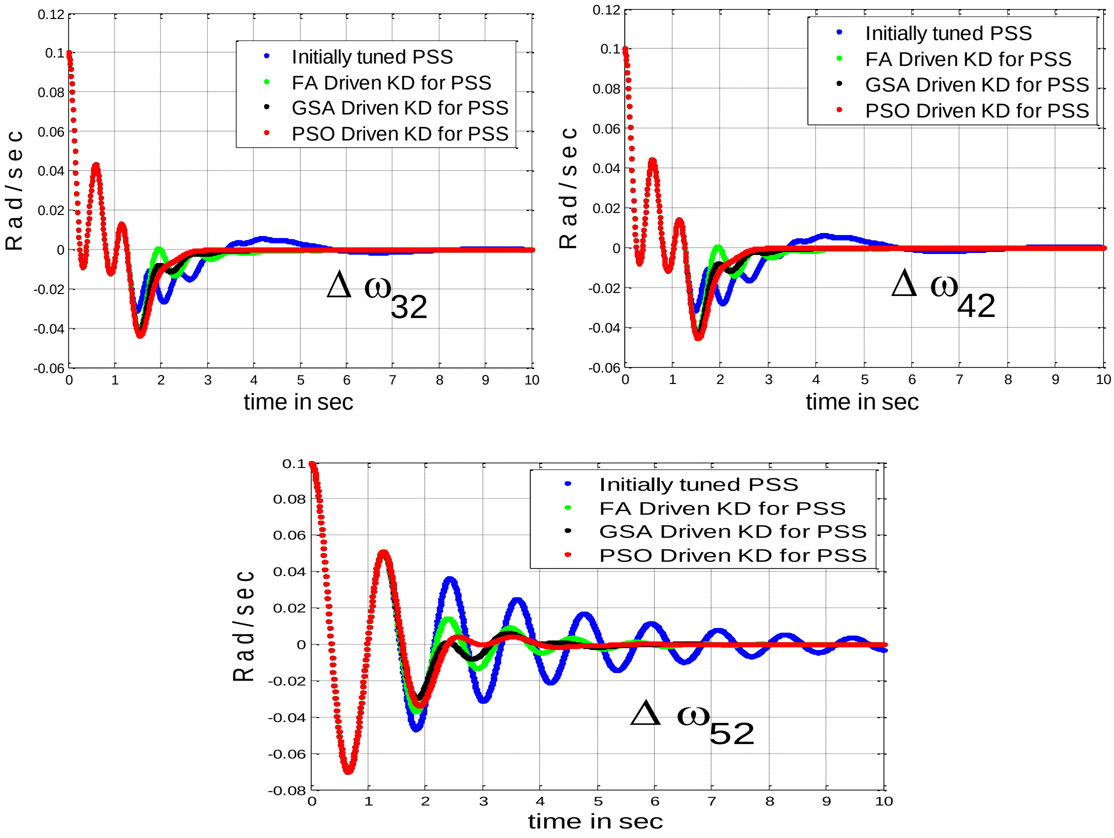
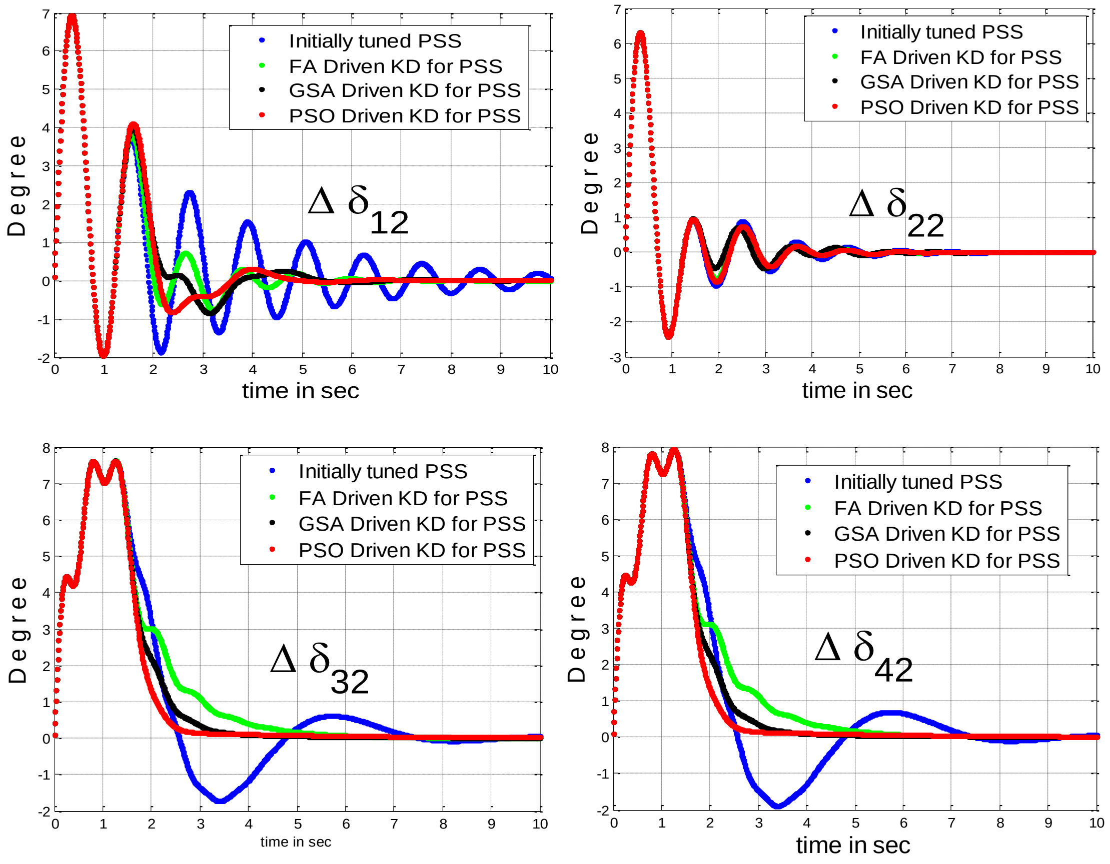


Figure 5.17 Angular speed deviation for all the generators connected in Area 2 (Case 5.11)



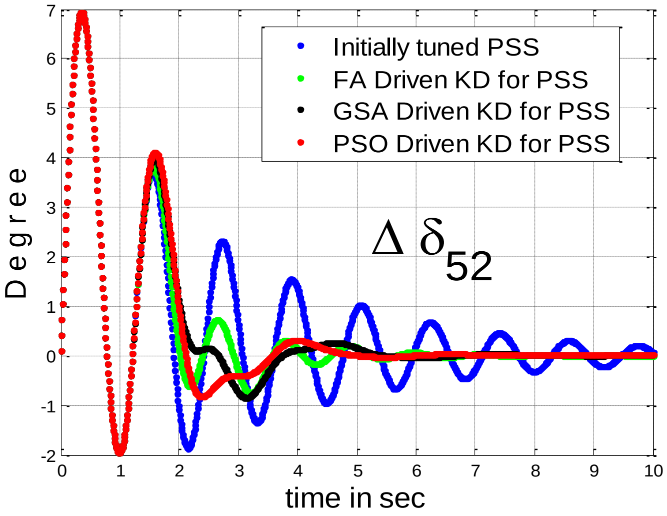


Figure 5.18 Phase angle deviation for all the generators connected in Area 2 (Case 5.11)

Table 5.18 Comparison of system response with all the three optimization techniques for Ten Area Fifty Machine system (Area 2) - Case 5.11

Case 5.11	**States**	**I.T.C.S.**	**F.A.D.C.S.**	**G.S.A.D.C.S.**	**P.S.O.D.C.S.**
(S.T.)	$\Delta\omega_{12}$	12.0	5.7	4.9	4.2
	$\Delta\omega_{22}$	5.8	5.8	5.8	5.7
	$\Delta\omega_{32}$	6.2	3.5	3.0	2.5
	$\Delta\omega_{42}$	6.2	3.5	3.0	2.5
	$\Delta\omega_{52}$	12.0	5.7	4.9	4.2
	$\Delta\delta_{12}$	12.0	6.2	6.1	5.0
	$\Delta\delta_{22}$	5.7	5.5	5.5	5.4
	$\Delta\delta_{32}$	8.2	4.5	3.5	3.1
	$\Delta\delta_{42}$	8.2	4.5	3.5	3.1
	$\Delta\delta_{52}$	12.1	6.2	6.1	5.0
(F.P.O.S.)	$\Delta\omega_{12}$	-.045	-0.04	-0.03	-0.031
	$\Delta\omega_{22}$	0.03	0.03	0.03	0.03
	$\Delta\omega_{32}$	-0.035	-0.042	-0.042	-0.042
	$\Delta\omega_{42}$	-0.35	-0.042	-0.042	-0.042
	$\Delta\omega_{52}$	-0.045	-0.04	-0.03	-0.031
	$\Delta\delta_{12}$	4.0	3.9	4.0	4.0

	$\Delta\delta_{22}$	1.0	1.0	1.0	1.0
	$\Delta\delta_{32}$	7.7	7.7	7.7	7.7
	$\Delta\delta_{42}$	7.7	7.7	7.7	7.7
	$\Delta\delta_{52}$	4.0	3.9	4.0	4.0

Table 5.19 Parameters of PSS tuned with all the optimization techniques in Area 2 at different operating conditions - Case 5.11

	T1(Time Constant)	**T2(Time Constant)**	**Kc(Gain)**
(I.T.C.S) Load L2(1) (G1+jB1)	T11=1.1166; T12=1.1632; T13=2.7500; T14=2.7500; T15=1.1166;	T21=2.0507; T22=0.3466; T23=.3798; T24=.3798; T25=2.0507;	Kc1=14.6821; Kc2=18.8107; Kc3=14.3051; Kc4=14.8146; Kc5=14.6821;
(F.A.D.C.S.) Load L2(2) (G2+jB2)	T11=0.9468; T12=1.0117; T13=0.1902; T14=0.1902; T15=0.9468;	T21=0.1524; T22=0.2822; T23=1.4057; T24=1.4057; T25=0.1524;	Kc1=6.7270; Kc2=19.4722; Kc3=5.0000; Kc4=5.0000; Kc5=6.7270;
(G.S.A.D.C.S.) Load L2(2) (G2+jB2**)**	T11=0.4886; T12=2.7227; T13=0.3112; T14=0.3112; T15=0.4886;	T21=0.1050; T22=0.3121; T23=0.1102; T24=0.1102; T25=0.1050;	Kc1=15.9319; Kc2=10.2015; Kc3=9.7339; Kc4=9.7339; Kc5=15.9319;
(P.S.O.D.C.S.) Load L2(2) (G2+jB2)	T11=0.5655; T12=1.9415; T13=0.2362; T14=0.2362; T15=0.5655;	T21=0.0598; T22=0.2950; T23=0.0598; T24=0.0598; T25=0.0598;	Kc1=6.4902; Kc2=9.3922; Kc3=12.6863; Kc4=12.6863; Kc5=6.4902;

Table 5.20 Eigenvalues of system matrix of Area 2 for all the optimization techniques with Case 5.11

Initially Tuned Controller	**FA Driven Controller**	**GSA Driven Controller**	**PSO Driven Controller**
Eigenvalues	**Eigenvalues**	**Eigenvalues**	**Eigenvalues**
-0.3279 + 5.3696i	-7.9066	-10.7754	-17.1474
-0.3279 - 5.3696i	-0.7851 + 5.7339i	-1.1897 + 5.9325i	-1.4397 + 5.4323i
-2.3045 + 1.2423i	-0.7851 - 5.7339i	-1.1897 - 5.9325i	-1.4397 - 5.4323i
-2.3045 - 1.2423i	-1.1814 + 1.9543i	-0.8285 + 2.1362i	-0.9910 + 2.3866i
-0.3484	-1.1814 - 1.9543i	-0.8285 - 2.1362i	-0.9910 - 2.3866i
-0.4662	-0.3139	-0.3038	-0.3055
-0.7273 + 5.6329i	-0.8832 + 5.7548i	-0.8095 + 6.0426i	-0.9176 + 5.6695i
-0.7273 - 5.6329i	-0.8832 - 5.7548i	-0.8095 - 6.0426i	-0.9176 - 5.6695i
-4.3073	-5.1759	-5.3288	-4.9320
-1.2453 + 3.2169i	-0.9846 + 3.2605i	-0.8142 + 2.9584i	-0.9954 + 3.3152i
-1.2453 - 3.2169i	-0.9846 - 3.2605i	-0.8142 - 2.9584i	-0.9954 - 3.3152i
-0.3261	-0.3254	-0.3211	-0.3250
-15.9642	-12.2950	-2.2715 + 8.5976i	-20.2085
-1.2461 +10.4599i	-1.5908 + 8.0289i	-2.2715 - 8.5976i	-3.5276 + 8.3630i
-1.2461 -10.4599i	-1.5908 - 8.0289i	-0.3193	-3.5276 - 8.3630i
-0.5627 + 1.3134i	-1.4541	-2.1718	-3.1897 + 1.5371i
-0.5627 - 1.3134i	-0.3407	-4.2078	-3.1897 - 1.5371i
-0.2788	-0.6675	-15.0602	-0.3068
-16.0516	-12.2950	-2.2715 + 8.5976i	-20.2085
-1.2257 +10.5230i	-1.5908 + 8.0289i	-2.2715 - 8.5976i	-3.5276 + 8.3630i
-1.2257 -10.5230i	-1.5908 - 8.0289i	-0.3193	-3.5276 - 8.3630i
-0.5400 + 1.3135i	-1.4541	-2.1718	-3.1897 + 1.5371i
-0.5400 - 1.3135i	-0.3407	-4.2078	-3.1897 - 1.5371i
-0.2775	-0.6675	-15.0602	-0.3068
-0.3279 + 5.3696i	-7.9066	-10.7754	-17.1474
-0.3279 - 5.3696i	-0.7851 + 5.7339i	-1.1897 + 5.9325i	-1.4397 + 5.4323i
-2.3045 + 1.2423i	-0.7851 - 5.7339i	-1.1897 - 5.9325i	-1.4397 - 5.4323i
-2.3045 - 1.2423i	-1.1814 + 1.9543i	-0.8285 + 2.1362i	-0.9910 + 2.3866i
-0.3484	-1.1814 - 1.9543i	-0.8285 - 2.1362i	-0.9910 - 2.3866i
-0.4662	-0.3139	-0.3038	-0.3055

Table 5.21 Cost function with all the three optimization techniques - Case 5.11

Objective Function (Fx)	**Firefly Algorithm**	**Gravitational Search Algorithm**	**Particles Swarm Optimization**
ITAE (G1)	0.8591	0.4907	0.3871
ITAE (G2)	0.6349	0.7051	0.6268
ITAE (G3)	0.2640	0.1316	0.0997
ITAE (G4)	0.2640	0.1316	0.0997
ITAE (G5)	0.8591	0.4907	0.3871
Time to develop K.D (in sec)	20.321	23.230	24.046

Table 5.18 shows the comparison of system responses between all the three optimization techniques in terms of overshoot/undershoot (after change in operating

condition at time t_2) and settling time (Overall Response). Control parameters of PSS (stored in knowledge domain) with different optimization techniques at respective loading are shown in Table 5.19. When actual loading condition arrives very near to the stored condition, control parameter up-gradation takes place in the controller by inference mechanism as set of rules. Table 5.20 shows eigenvalues for all states variables in area 2 for all the three optimization techniques and without retuning the controller parameters (initially tuned values). Table 5.21 shows the objective function minimized by optimization techniques for specific system operating conditions (i.e. at Load L2 (2)). This concept shows that when system operating condition changes with time, retuning (parameter up-gradation) of respective control from the knowledge domain will enhance oscillation damping in the system, and therefore, enhance stability of the system. Table 5.21 also shows the time taken by each optimization techniques to develop knowledge domain for each operational shift in the system.

5.2.2 Control Sharing Concept

Sample Six Area Test System:

STATCOM-as supplementary controller in addition to existing controller:

This section represents effectiveness of STATCOM connected in the network when PSS approaches to the onset of unacceptable behavior of network at certain system operating condition, thus validating the concept of control sharing in the system. PSS plus STATCOM combined altogether modulates power flow in the network as desired and brings the system in stable domain. Sample six area system has been considered with STATCOM connected between area 3 and area 4 and PSS to all the generators as shown in Figure 5.19. Time constants (T1 and T2) of lead-lag phase compensation block and gain (Kc) are used as the control parameters for PSS and amplitude modulation ratio (m_e) and phase angle (δ_e) as the control parameters for STATCOM.

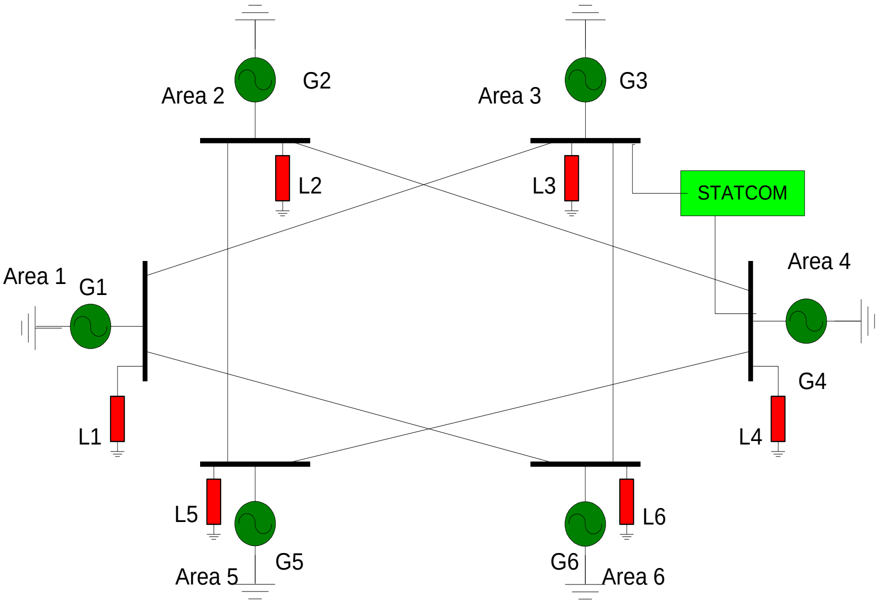
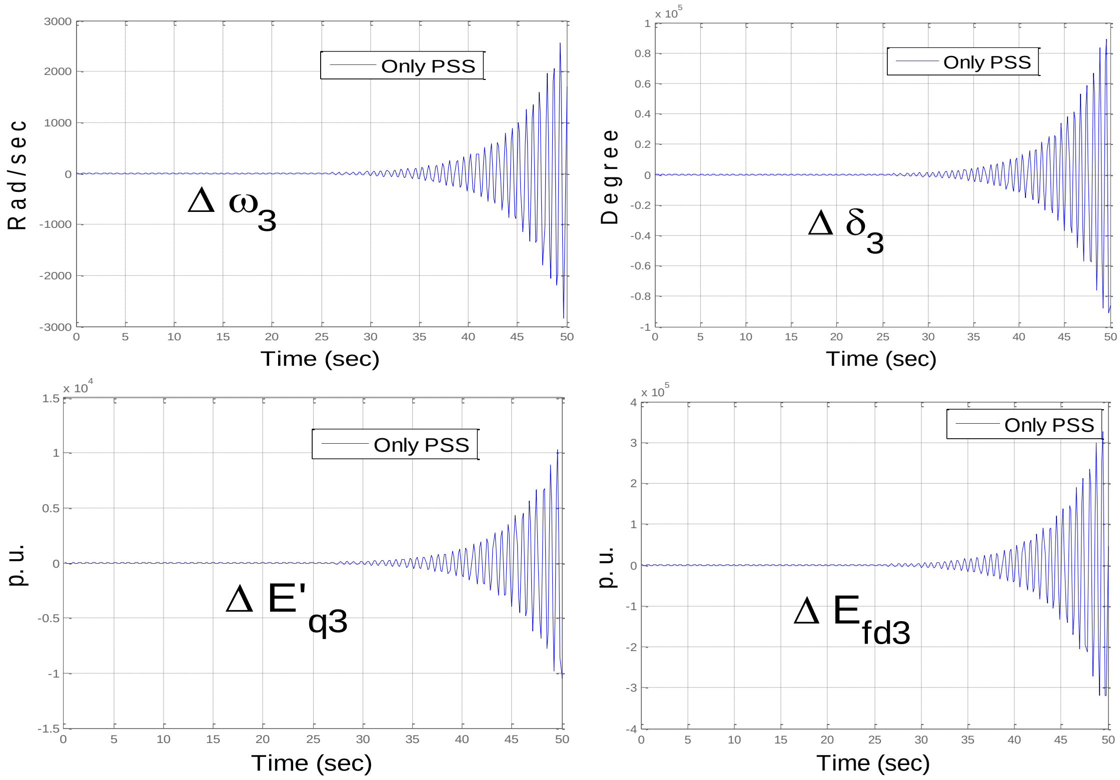


Figure 5.19 Sample Six Area system with STATCOM between area 3 and 4

Load in Area 3 (Y3)=G3+jB3; where G3=1.6615; B3=1.9029;

Case 5.12=L3(3)=1.7*Y3 (**1-** PSS only / **2-** STATCOM supplements PSS)



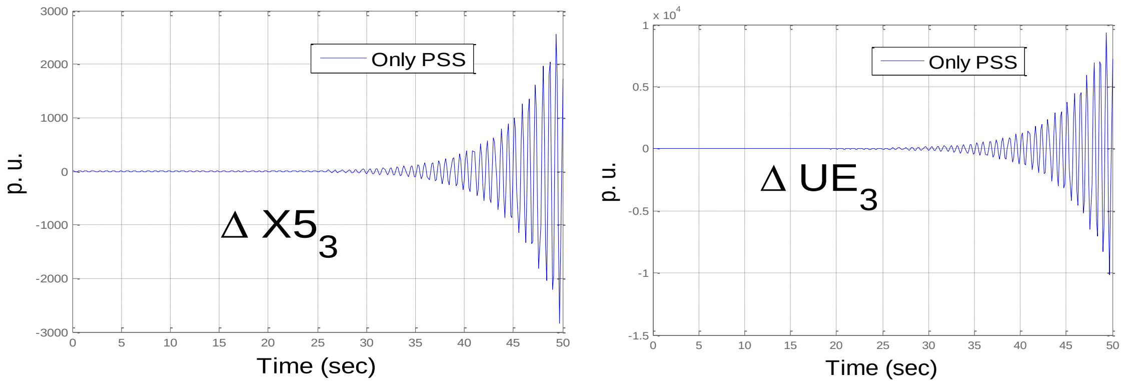


Figure 5.20 Perturbation responses of system states for Case 5.12 for Six Area system with PSS only (Area 3)

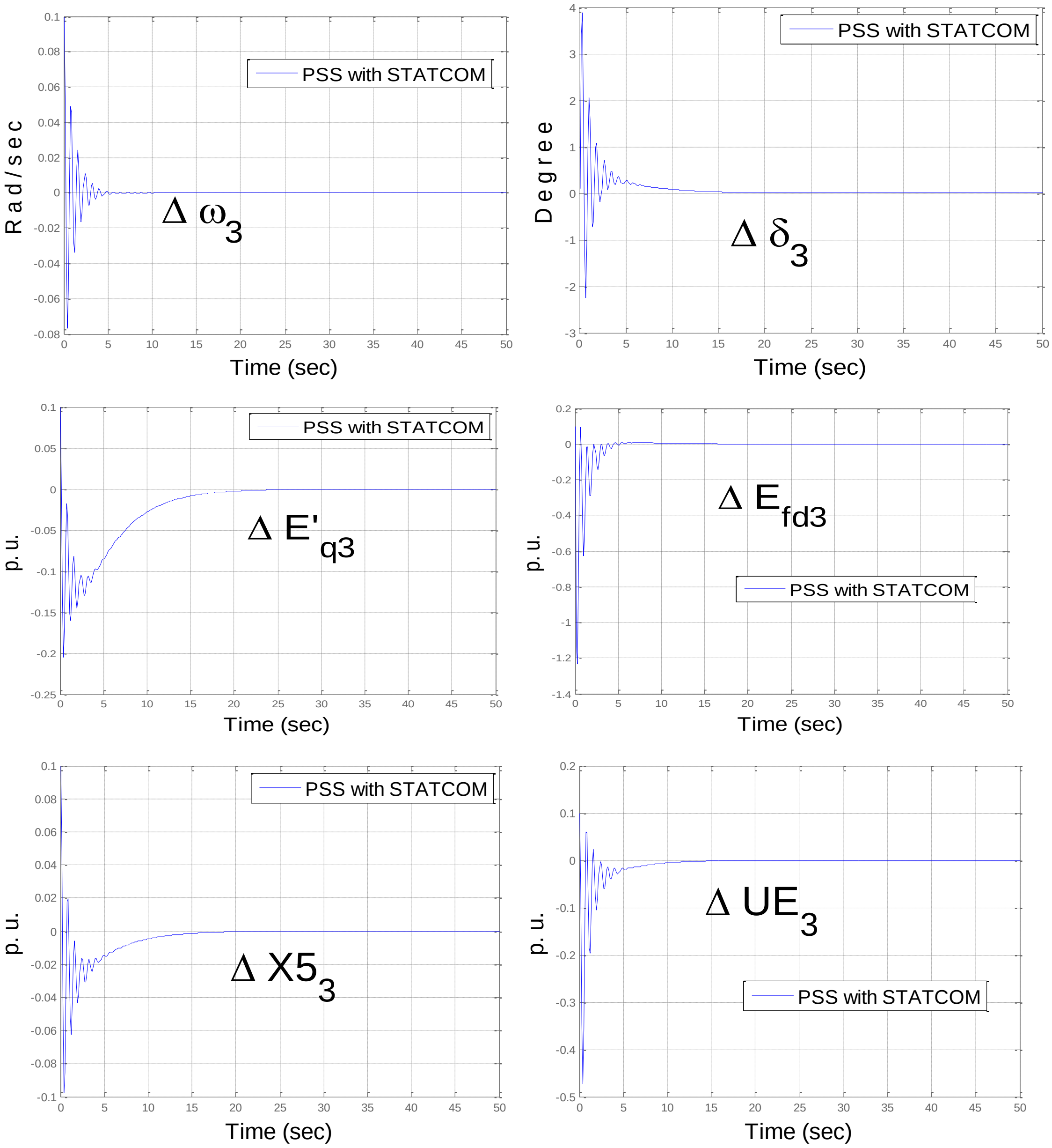


Figure 5.21 Perturbation responses of system states for Case 5.12 for Six Area system with STATCOM supplements PSS (Area 3)

Table 5.22 Comparison of system response for Six Area system (Area 3) - Case 5.12

System	**State**	**Over-shoot**	**Settling time**	**Eigenvalues**
Case 5.12 PSS Fails to Stabilize even with knowledge domain inference mechanism	$\Delta\omega_3$	---	---	-15.0770
	$\Delta\delta_3$	---	---	**0.2115 + 8.9028i**
	$\Delta E'_{q3}$	---	---	**0.2115 - 8.9028i**
	ΔE_{fd3}	---	---	-2.4103 + 0.8128i
	$\Delta X5_3$	---	---	-2.4103 - 0.8128i
	ΔUE_3	---	---	-0.1256
Case 5.12 STATCOM as supplementary controller with PSS	$\Delta\omega_3$	-0.08	5.0	-5787.400
	$\Delta\delta_3$	3.90	8.0	-0199.800
	$\Delta E'_{q3}$	-0.20	17.0	-0.900 + 7.8000i
	ΔE_{fd3}	-1.20	5.0	-0.900- 7.8000i
	$\Delta X5_3$	-0.10	12.0	-2.200 + 6.000i
	ΔUE_3	-0.46	8.0	-2.200 - 6.000i

Table 5.22 shows comparison between system responses in terms of overshoot/undershoot and settling time for tuned PSS only, and also when STATCOM supplements PSS functioning at certain operating conditions in situations PSS alone could not respond perturbation existing in the system. Figure 5.20 shows system response with PSS alone for specific system operating condition where system approaches to the onset of unacceptable behavior and fails to damp oscillations owing to perturbation. In that system operating conditions STATCOM acts as supplementary controller in addition to the existing PSS by sharing extra burden and stabilize the system as quickly as possible (shown in Figure 5.21). Thus STATCOM used as an ancillary service in addition to the existing local controller and thus helps to restore system by regulating desired power flow in the system.

SSSC - as Supplementary Controller to PSS by Increasing ATC of the Line:

To demonstrate effectiveness of the proposed control sharing concept, another case has been considered using SSSC as a supplementary controller in addition to PSS by emulating the reactance in transmission line that increases the Available Transfer Capability (ATC) of line, which in turn stabilizes the overall system (refer Figure 5.22). Time constants (T1 and T2) of lead-lag compensation block and gain (Kc) are used as control parameters for PSS, whereas amplitude modulation ratio (m_b) and phase angle (δ_b) are the SSSC control parameters.

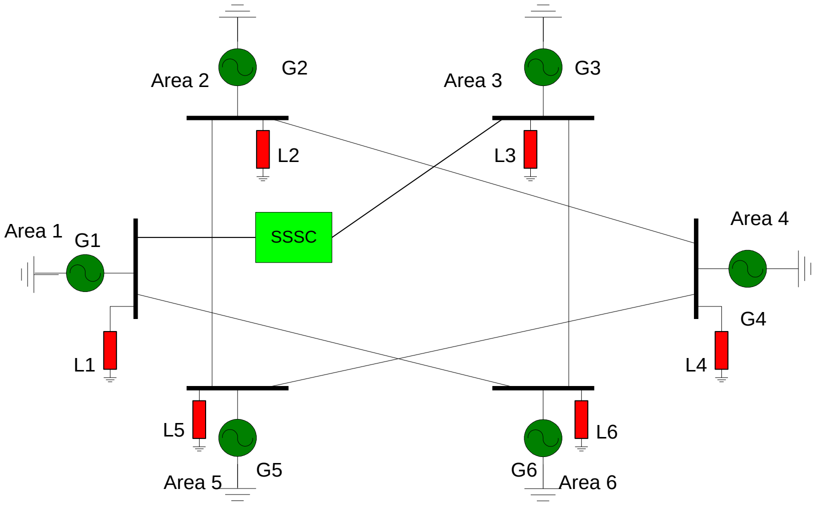


Figure 5.22 Six Area system with SSSC between area 1 and 3

When Length of the transmission line increases certain value, even retuning of PSS fails to stabilize the system, as system states demonstrate unstable response, under this situation SSSC acts as supplementary controller to existing PSS by enhancing available transfer capability of the line and thus brings back stable states.

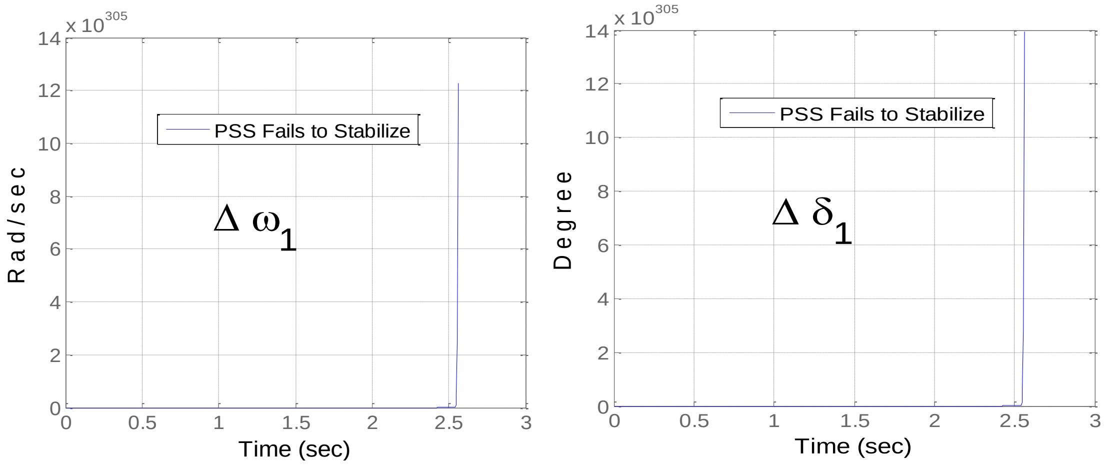
Transmission line length between area 1 and area 3 (Z13)=R13+jX13; where R13=0.034; X13=0.6; here, R13 and X13 are the resistance and reactance of the transmission line between area 1 and 3 respectively.

Case 5.13- Z13(3)=4.9*Z13 (**1-** PSS Only / **2-** SSSC supplements PSS)

Table 5.23 shows the comparison between system response with PSS only, and SSSC supplements PSS by reducing the reactance of the transmission line and thus increasing ATC of the line. Comparison has been done in terms of overshoot and settling time for both controllers. Figure 5.23 shows the failure of PSS for Case 5.13. Performance of SSSC as a supplementary controller assisting PSS has been shown in Figure 5.24 which brings the system back to stable operating point by damping oscillations quickly. This shows the complete hierarchy of control structure from local to global controller.

Table 5.23 Overshoot, settling time and eigenvalues for PSS only and PSS with SSSC - Case 5.13

System	**State**	**Over-shoot**	**Settling time**	**Eigenvalues**
Case 5.13 PSS Fails to Stabilize even with KDIM	$\Delta\omega_1$	---	---	**276.0934**
	$\Delta\delta_1$	---	---	-106.9382
	$\Delta E'_{q1}$	---	---	-4.3526
	ΔE_{fd1}	---	---	-0.6754
	$\Delta X5_1$	---	---	-0.6164
	ΔUE_1	---	---	-0.1243
Case 5.13 PSS with SSSC to increase ATC of the T. Line m_b= 0.7758 δ_b= 0.0010	$\Delta\omega_1$	0.05	2.1	-734610.0
	$\Delta\delta_1$	-0.2	3.1	-660.0 + 600.0i
	$\Delta E'_{q1}$	0.27	3.5	-660.0 - 600.0i
	ΔE_{fd1}	-1.1	5.1	-380. 0
	$\Delta X5_1$	0.18	25	-120.0
	ΔUE_1	3.5	3.5	-20.0



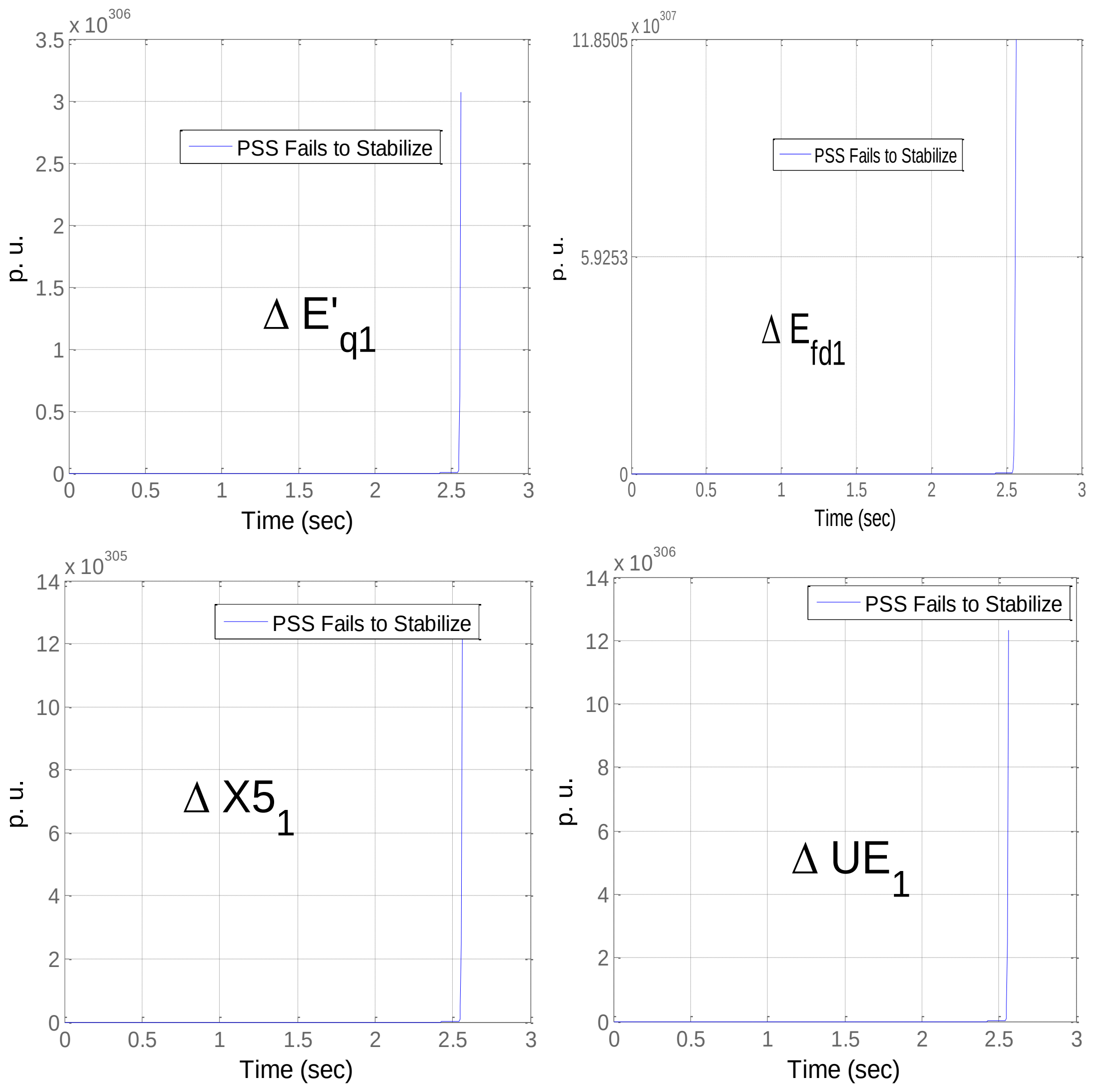
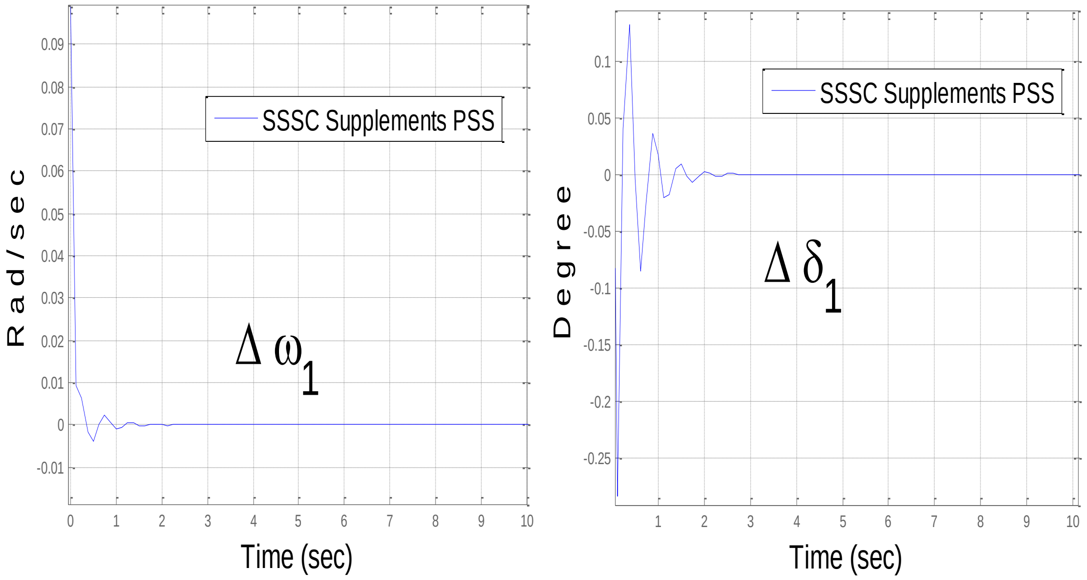


Figure 5.23 States response when PSS fails to stabilize as line length of transmission line increases (Case 5.13)



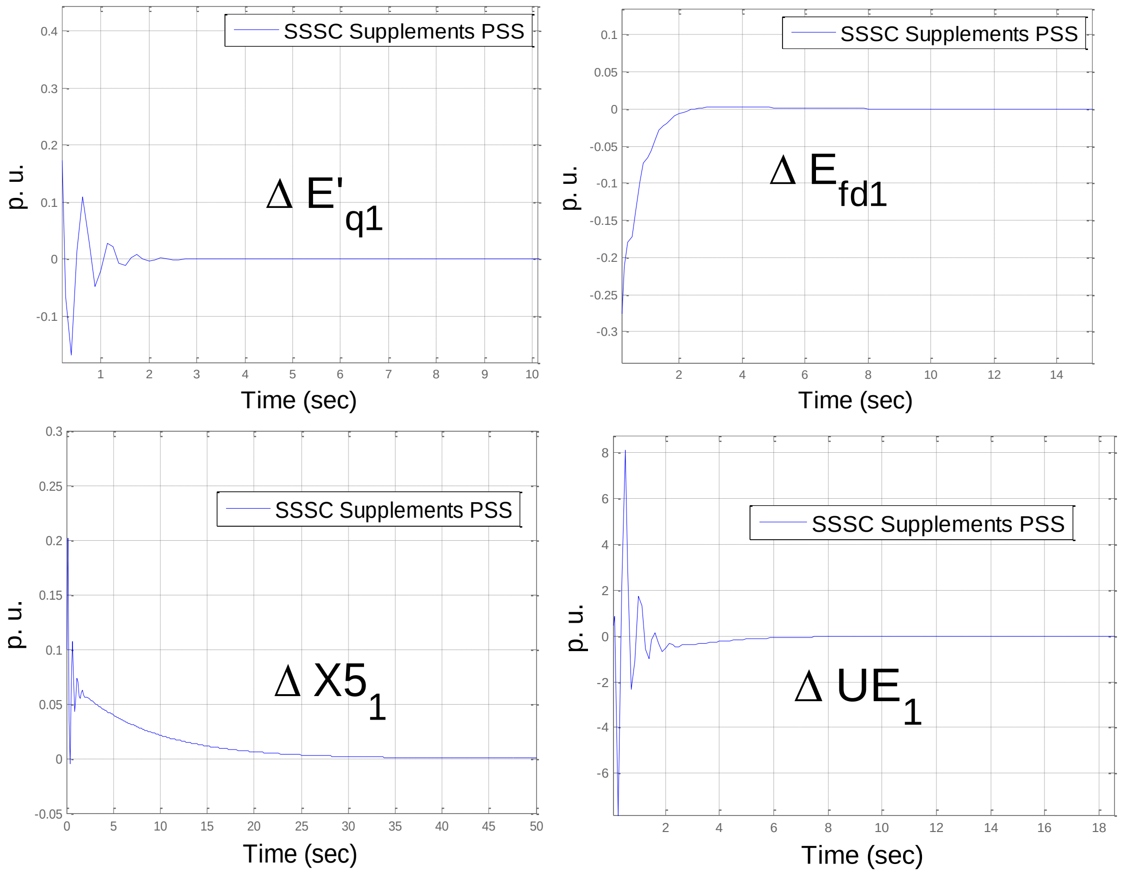


Figure 5.24 States response of PSS with SSSC (Case 5.13)

Results have been simulated for six area system with change in reactance of the transmission line and its effect on state variables in area 1 has been noticed. At specific operating condition (shown in case 5.13) SSSC acts as supplementary controller, which emulates the reactance of line and make system state variables stable.

UPFC- as supplementary controller in addition to the existing PSS controller:

Control sharing concept includes the supplementary controller (FACTS devices) which assist existing local controller that is on the verge of instability due to extreme loading conditions. The initially tuned PSS for specific operating point fails to perform satisfactorily due to the limitation of controller range. In situations, network is having UPFC quickly modulates the real and reactive power exchanges arising due to the operational shift and assist PSS to recover. The coordinative strategy may be viewed as the instant of PSS failure and introduction of UPFC based power modulation for effective oscillation damping (refer Figure 5.25).

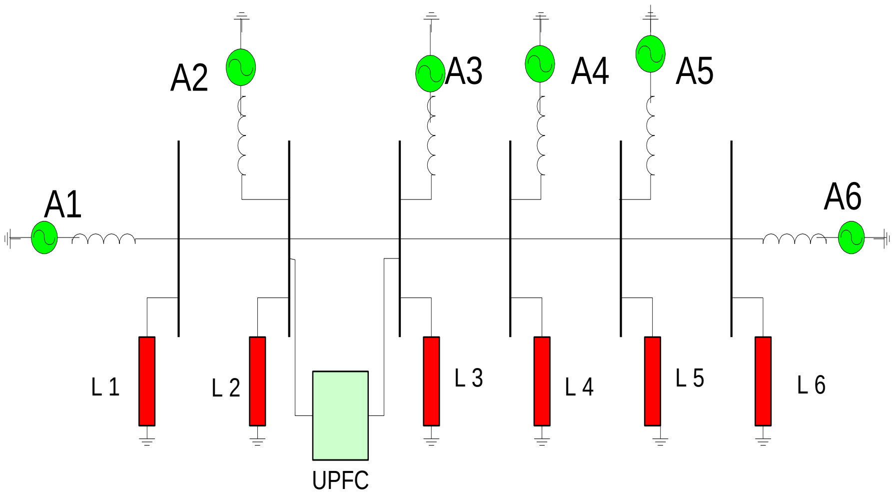
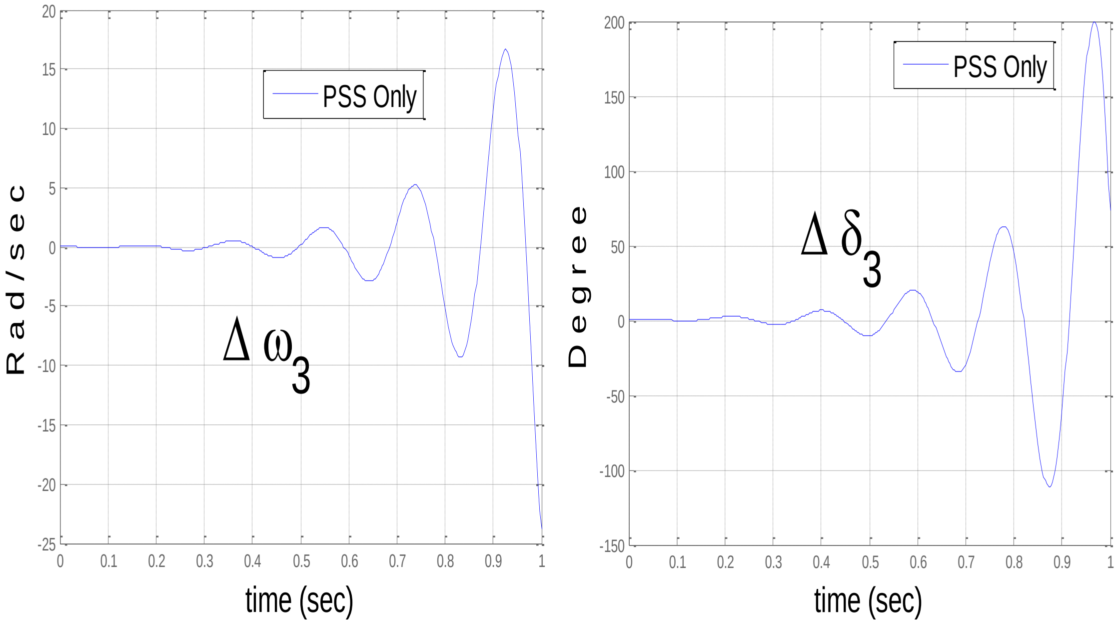


Figure 5.25 Sample Six Area test system 1

In this case study one operating condition has been created (increase in load) for area 3 so that PSS fails to stabilize the network (even with PSO driven knowledge domain concept), then UPFC acts as the supplementary controller and stabilizes the system. Figure 5.26 shows the unstable response of system states variables of area 3 when load is Ld2 (G3=1.7408 and B1=0.6221) (Case 5.14).



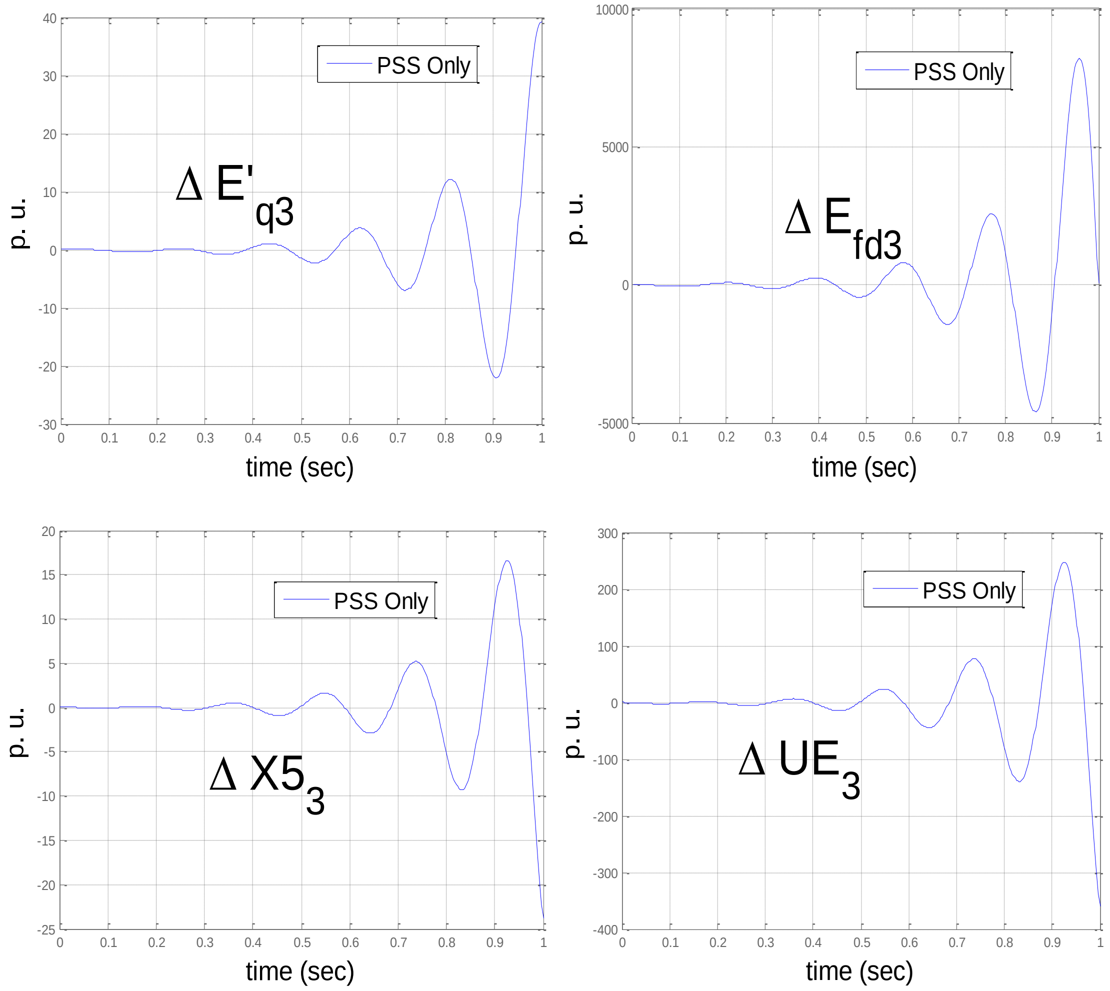


Figure 5.26 Perturbation response of system states with load (Ld2) for Area 3 (only PSS) (Case 5.14)

Table 5.24: System responses with PSS only and PSS with UPFC (Area 3) - Case 5.14

System	**State**	**Over-shoot**	**Settling time**	**Eigenvalues 1.0e+02***
PSS Only	$\Delta\omega_3$	---	---	-0.0103
	$\Delta\delta_3$	---	---	0.0000
T113=1.0276;	$\Delta E'_{q3}$	---	---	-0.0001
T213=1.2828;	ΔE_{fd3}	---	---	-0.0009
Kc13=18.7330;	$\Delta X5_3$	---	---	-0.0016
	ΔUE_3	---	---	-0.0014
PSS with UPFC	$\Delta\omega_3$	0.41	0.15	-1.344
	$\Delta\delta_3$	0.44	1.70	-0.955
m_e=0.0039	$\Delta E'_{q3}$	0.42	0.15	-0.055
δ_e=0.0196	ΔE_{fd3}	0.45	1.60	-0.024
m_b=0.2784	$\Delta X5_3$	0.15	15.0	-0.001
δ_b= 0.7176	ΔUE_3	0.255	3.1	-0.003

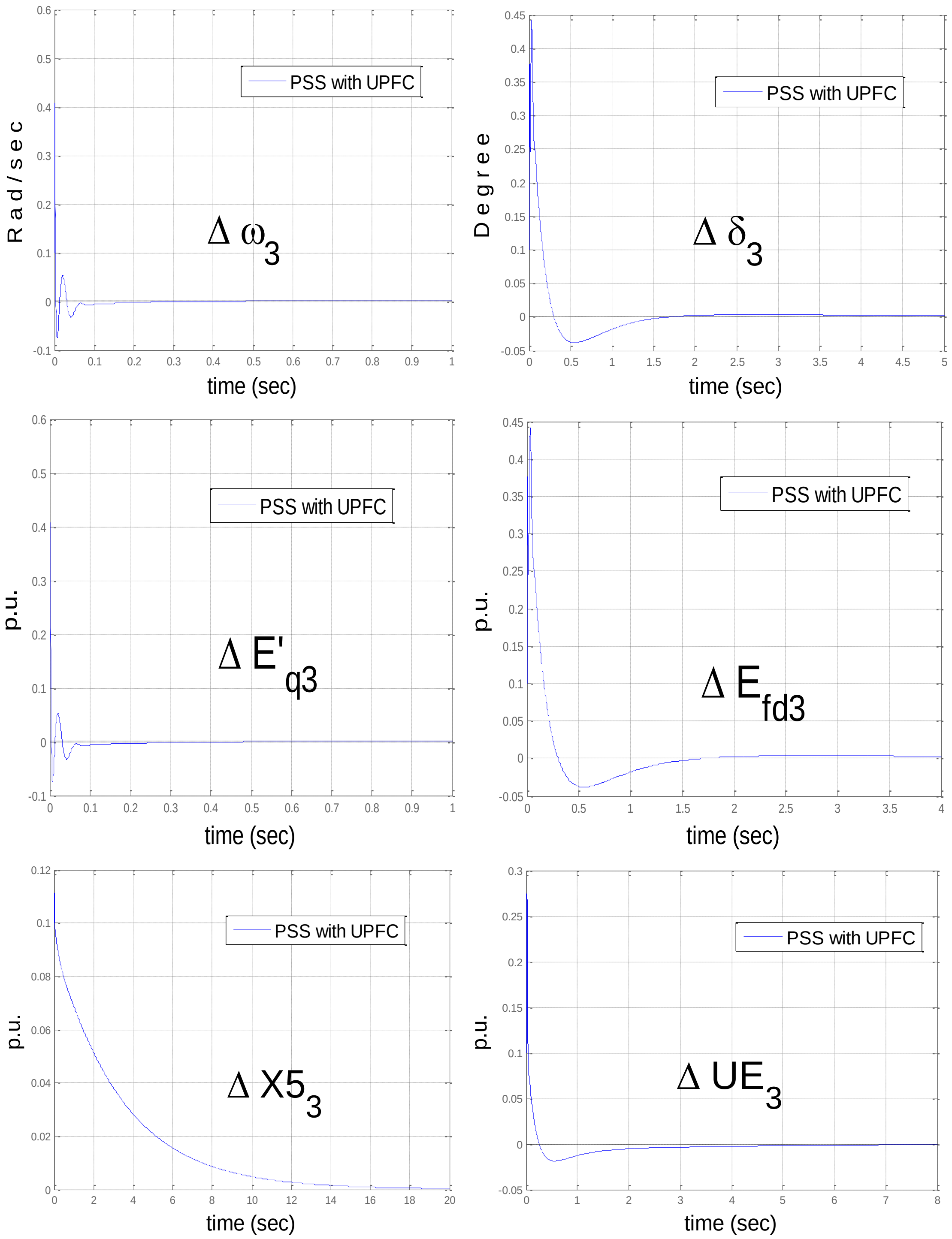


Figure 5.27 Perturbation response of system states with load (Ld2) for Area 3 (PSS with UPFC) (Case 5.14)

Table 5.24 shows the control parameters for PSS as well as UPFC and also settling time, overshoot and eigenvalues of the system for case 5.14. Figure 5.26 shows the operating conditions of the system with PSS only. Figure 5.27 shows states response at the same operating condition with UPFC acting as supplementary controller to PSS and thus stabilizes the system as quickly as possible. These figures demonstrate the effectiveness of proposed control concept at different operating conditions. The failure of the main controller (PSS) is primarily due to improper parameters setting (i.e. controller limitation). The supplementary controller (UPFC) functionality has been used to relax the main controller (PSS) for unacceptable operational shift by way of regulating real and reactive power in power network at the point of location, and nearby as well and thus helps to stabilize PSS. All the controllers parameters are tuned by PSO optimization technique as shown previously, among all the three optimization techniques PSO shows the improved results in terms of system stability and oscillation damping.

Sample Ten Area Fifty Machine Test System:

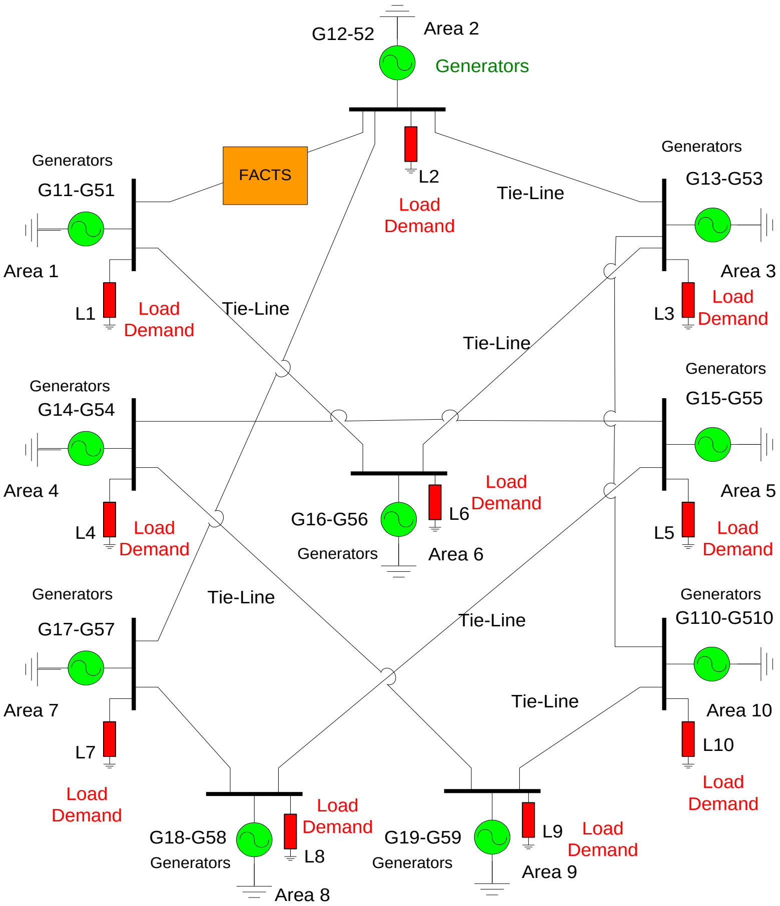


Figure 5.28 Ten Area Fifty Machines power system - PSS with each generator

UPFC - as supplementary controller in addition to the existing PSS controller:

Case 5.15: In this case study one operating condition has been created (increase in load) for area 2 so that PSS fails to stabilize the network (even with knowledge domain concept), then UPFC has been integrated as the supplementary controller and thus stabilizes system. PSS shows the unstable response of system states variables for area 2 when load is Ld2 (G2=5.5660; B2=6.2763 and increase in load with 4.5 times (Case 5.15).

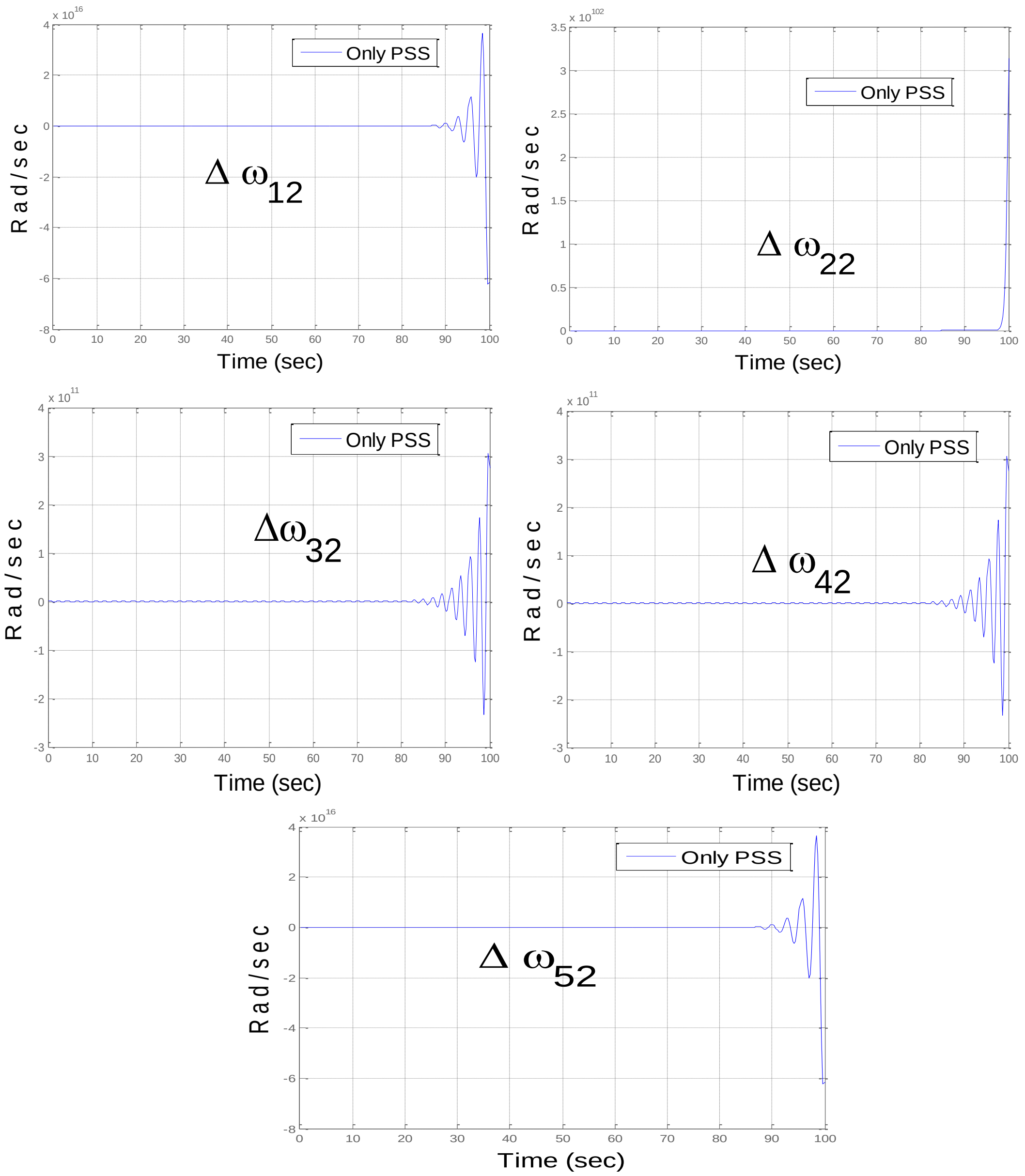


Figure 5.29 Angular speed deviation for all the generators connected in Area 2 with PSS only (Case 5.15)

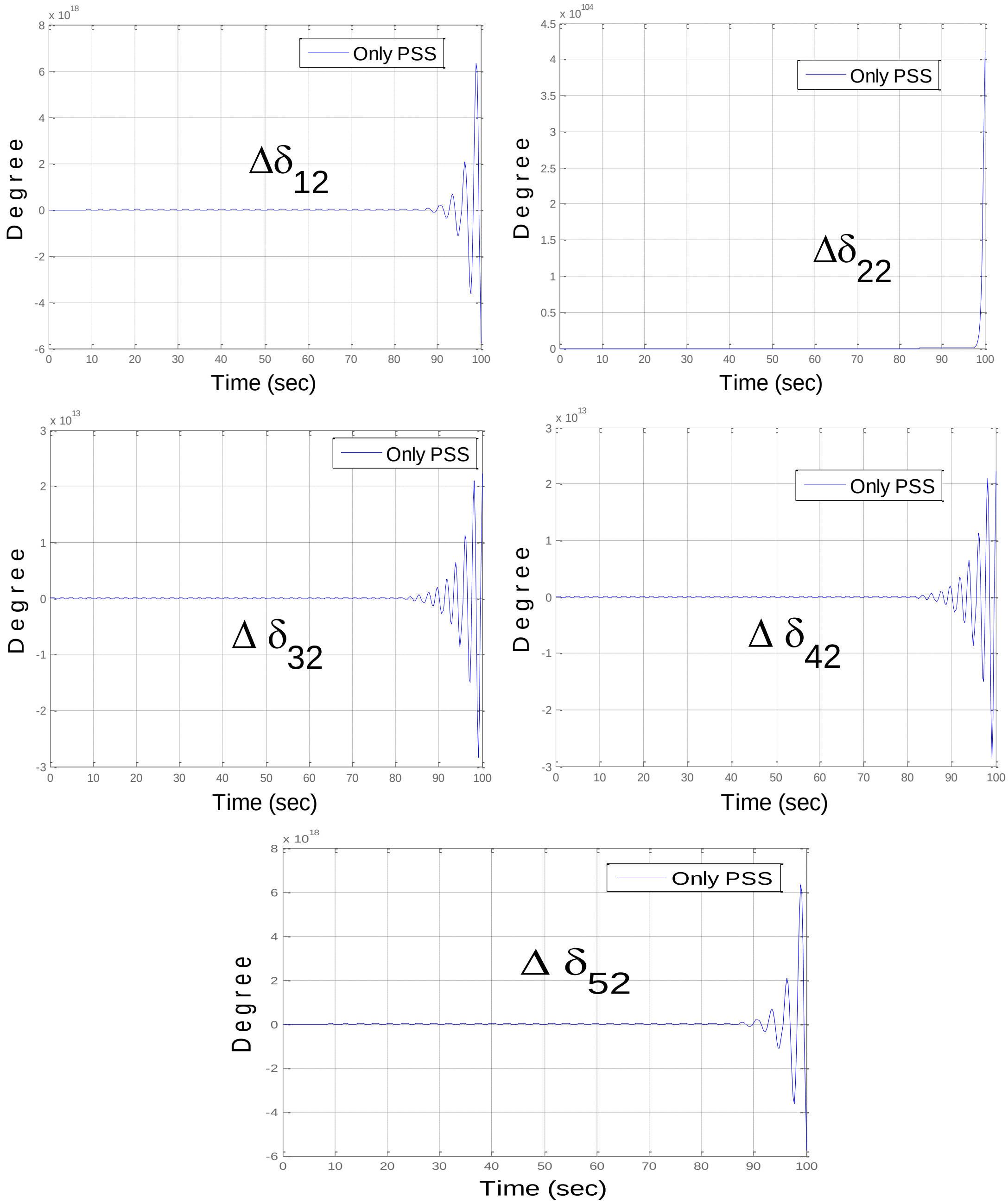
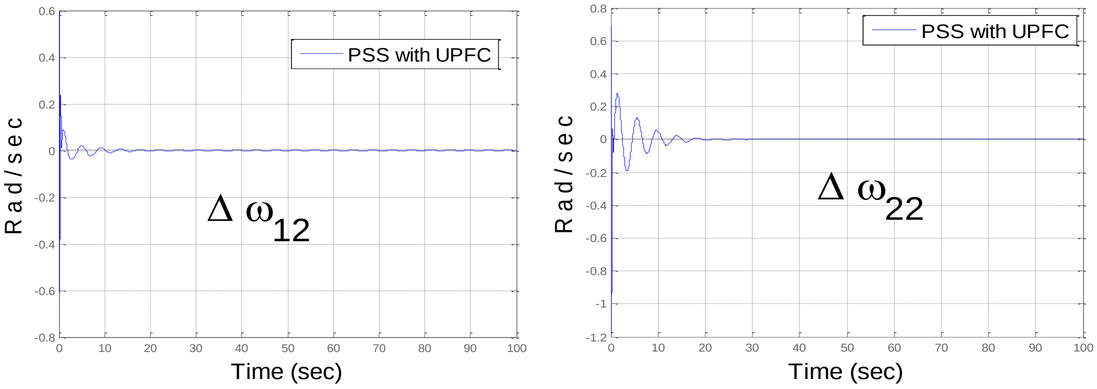


Figure 5.30 Phase angle deviation for all the generators connected in area 2 with PSS only (Case 5.15)



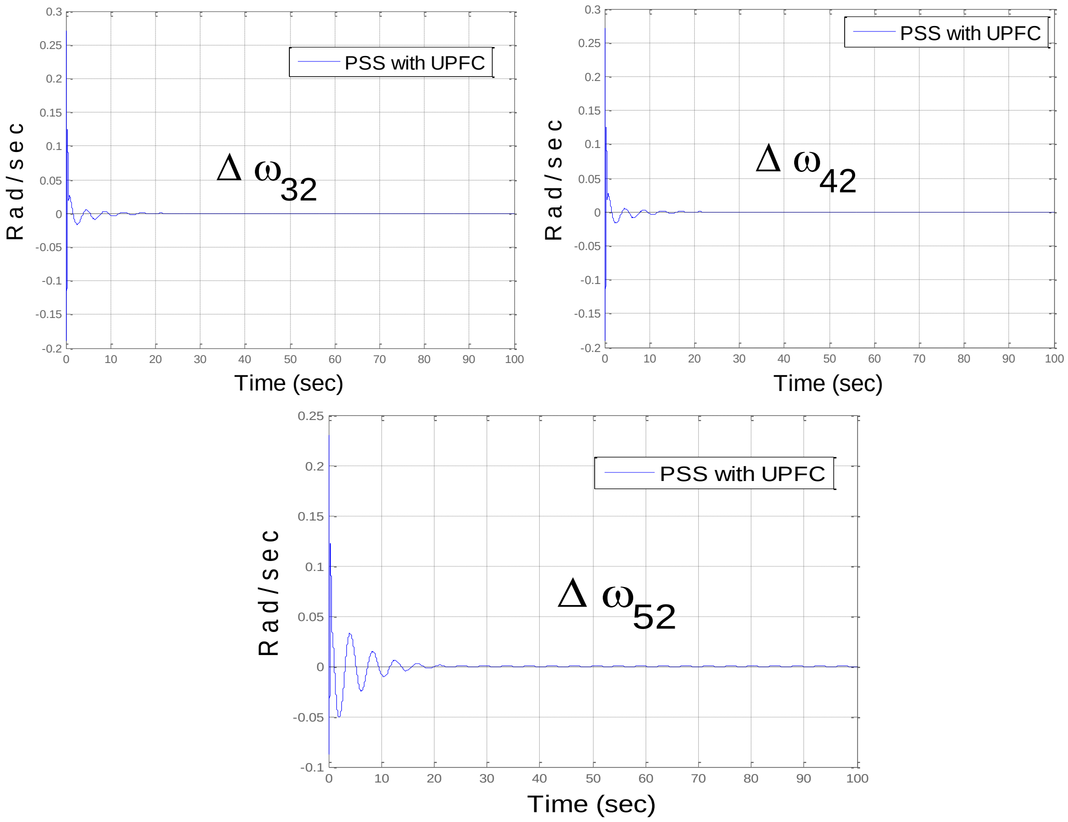
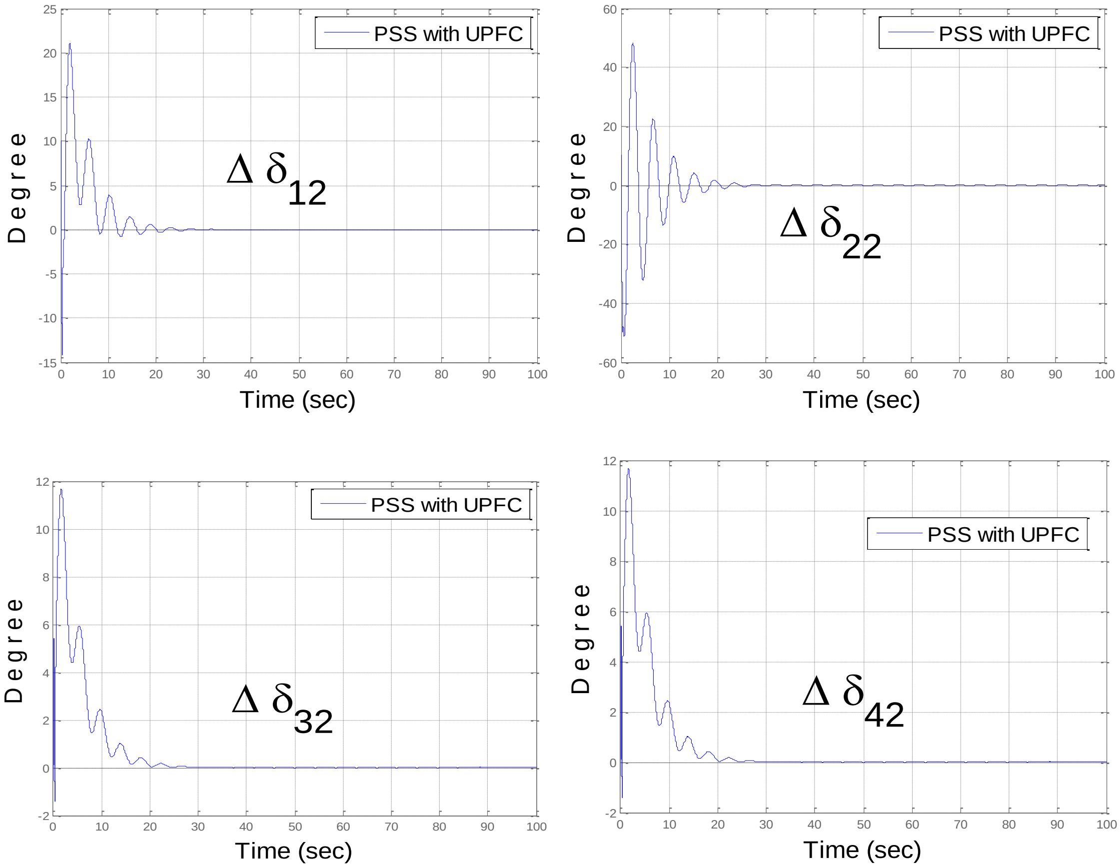


Figure 5.31 Angular speed deviation for all the generators connected in Area 2 with UPFC supplements PSS (Case 5.15)



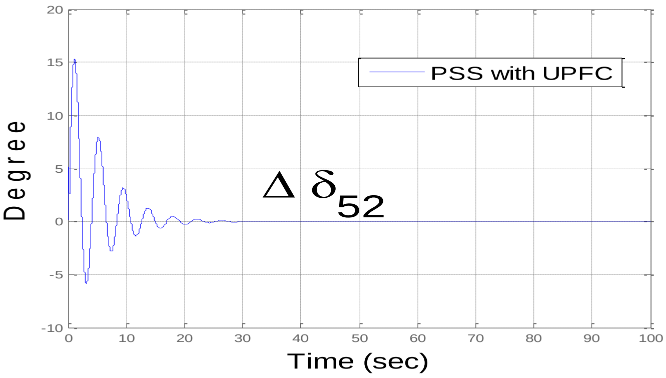


Figure 5.32 Phase angle deviation for all the generators connected in Area 2 with UPFC supplements PSS (Case 5.15)

Table 5.25 Eigenvalues of system matrix of Area 2 with only PSS and PSS with UPFC - Case 5.15

PSS Controller Only	**PSS with UPFC Controller**
Eigenvalues	Eigenvalues
-5.7503	-0.7882 + 3.9479i
-1.0481 + 3.2061i	-0.7882 - 3.9479i
-1.0481 - 3.2061i	-0.7460 + 3.9092i
0.4082 + 2.2409i	-0.7460 - 3.9092i
0.4082 - 2.2409i	-0.5031 + 2.7973i
-0.3002	-0.5031 - 2.7973i
-2.2883 + 4.3133i	-3.2818
-2.2883 - 4.3133i	-2.9771
2.3884	-2.5801
-3.2502	-0.1120 + 1.8000i
-0.4533	-0.1120 - 1.8000i
-0.3616	-0.2652 + 1.4413i
-15.3642	-0.2652 - 1.4413i
-1.8498 + 4.3254i	-0.1983 + 1.4857i
-1.8498 - 4.3254i	-0.1983 - 1.4857i
0.2803 + 2.9648i	-1.5388
0.2803 - 2.9648i	-0.1896 + 0.9681i
-0.3024	-0.1896 - 0.9681i
-15.3642	-0.6049
-1.8498 + 4.3254i	-0.6071
-1.8498 - 4.3254i	-0.4122
0.2803 + 2.9648i	-0.1780
0.2803 - 2.9648i	-0.1943
-0.3024	-0.3268
-5.7503	-0.3205
-1.0481 + 3.2061i	-0.3191
-1.0481 - 3.2061i	-0.2837
0.4082 + 2.2409i	-0.2761
0.4082 - 2.2409i	-0.2524
-0.3002	-0.2535

Table 5.26 Settling time and overshoot for Area 2 - Case 5.15

Case I	**States**	**Only PSS**	**PSS with UPFC**
(S.T.)	$\Delta\omega_{12}$	---	10.00
	$\Delta\omega_{22}$	---	17.00
	$\Delta\omega_{32}$	---	10.00
	$\Delta\omega_{42}$	---	9.00
	$\Delta\omega_{52}$	---	15.00
	$\Delta\delta_{12}$	---	18.00
	$\Delta\delta_{22}$	---	19.00
	$\Delta\delta_{32}$	---	20.00
	$\Delta\delta_{42}$	---	21.00
	$\Delta\delta_{52}$	---	20.00
(F.P.O.S.)	$\Delta\omega_{12}$	---	-00.50
	$\Delta\omega_{22}$	---	-01.10
	$\Delta\omega_{32}$	---	-00.19
	$\Delta\omega_{42}$	---	-00.18
	$\Delta\omega_{52}$	---	-00.09
	$\Delta\delta_{12}$	---	-15.00
	$\Delta\delta_{22}$	---	-35.00
	$\Delta\delta_{32}$	---	11.00
	$\Delta\delta_{42}$	---	11.80
	$\Delta\delta_{52}$	---	15.00

Study has been carried out when PSS fails to stabilize the system at certain system operating conditions. In that case, UPFC connected in the system will act as supplementary controller in addition to existing controller and thus stabilizes the system. The state variables deviation with PSS only and PSS with UPFC for the area 2 have been studied in Case 5.15. The initially tuned PSS fails to stabilize due to its limitation, whereas UPFC quickly modulates real and reactive power exchanges with operational shift in system and thus helps to recover PSS. Table 5.25 shows eigenvalues of system with PSS only, and PSS with UPFC at specific operating condition. It is clear from Table 5.25 that at certain operating condition eigenvalues of system matrix shifts from left to right side of the complex plane with PSS acting alone which is indicative of unstable system. Table 5.26 shows overshoot and settling time of area 2 and Figures 5.29-5.30 show the unstable response of system states variables of area 2 when load is increased to certain value (case 5.15), whereas Figures 5.31-5.32 represent the system perturbation state variables response when UPFC acts as supplementary controller for PSS and thus brings the system back to stable mode.

5.2.3 Validation in PSCAD Software

Two Area Four Machine Test System:

To validate the proposed controller parameter's up-grading and shifting/sharing concept, well-known PSCAD/EMTDC software has been used other than MATLAB. The results of PSCAD software also validates same concept and shows effectiveness of proposed concept to increase the stability and reliability of system. Two Area Four Machine Test system has been developed in both MATLAB and PSCAD software using same data set (Appendix A). Figures 5.33 (a)-5.33 (b) show the structure of two area four machine test system developed in PSCAD software while Figure 5.34 shows the representation of the same model in MATLAB using state space modeling as given in chapter 3.

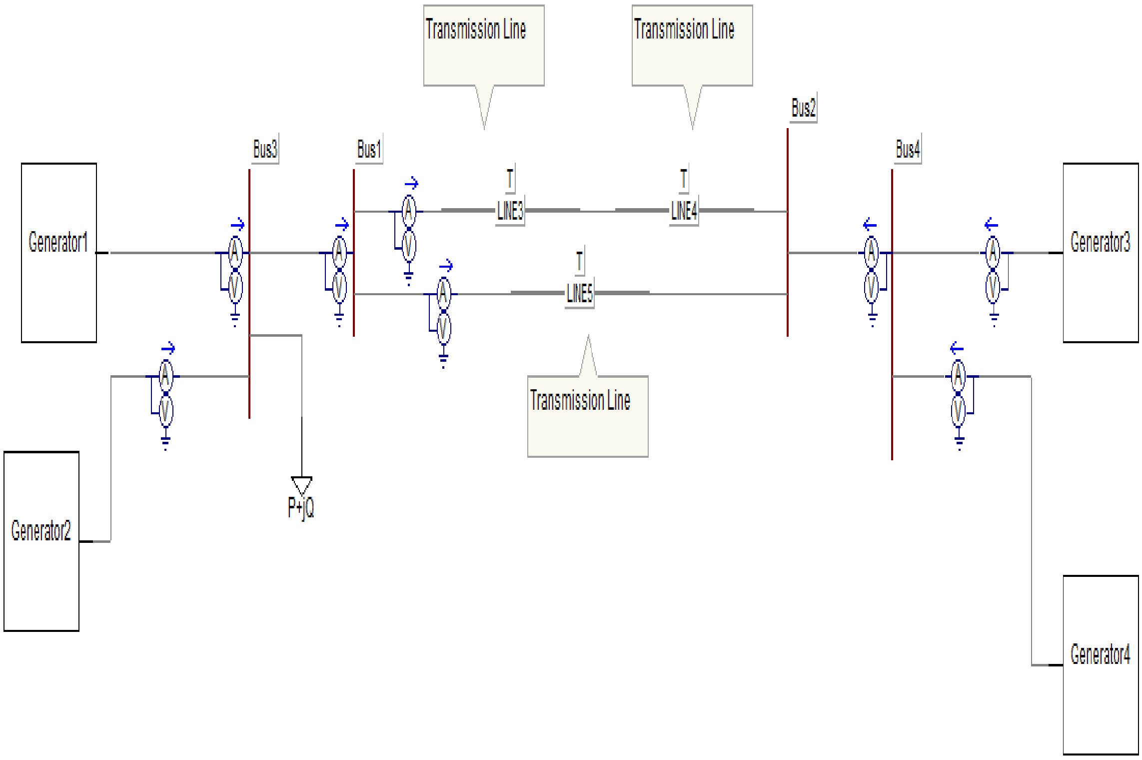


Figure 5.33 (a) PSCAD/EMTDC model of Two Area Four Machine system

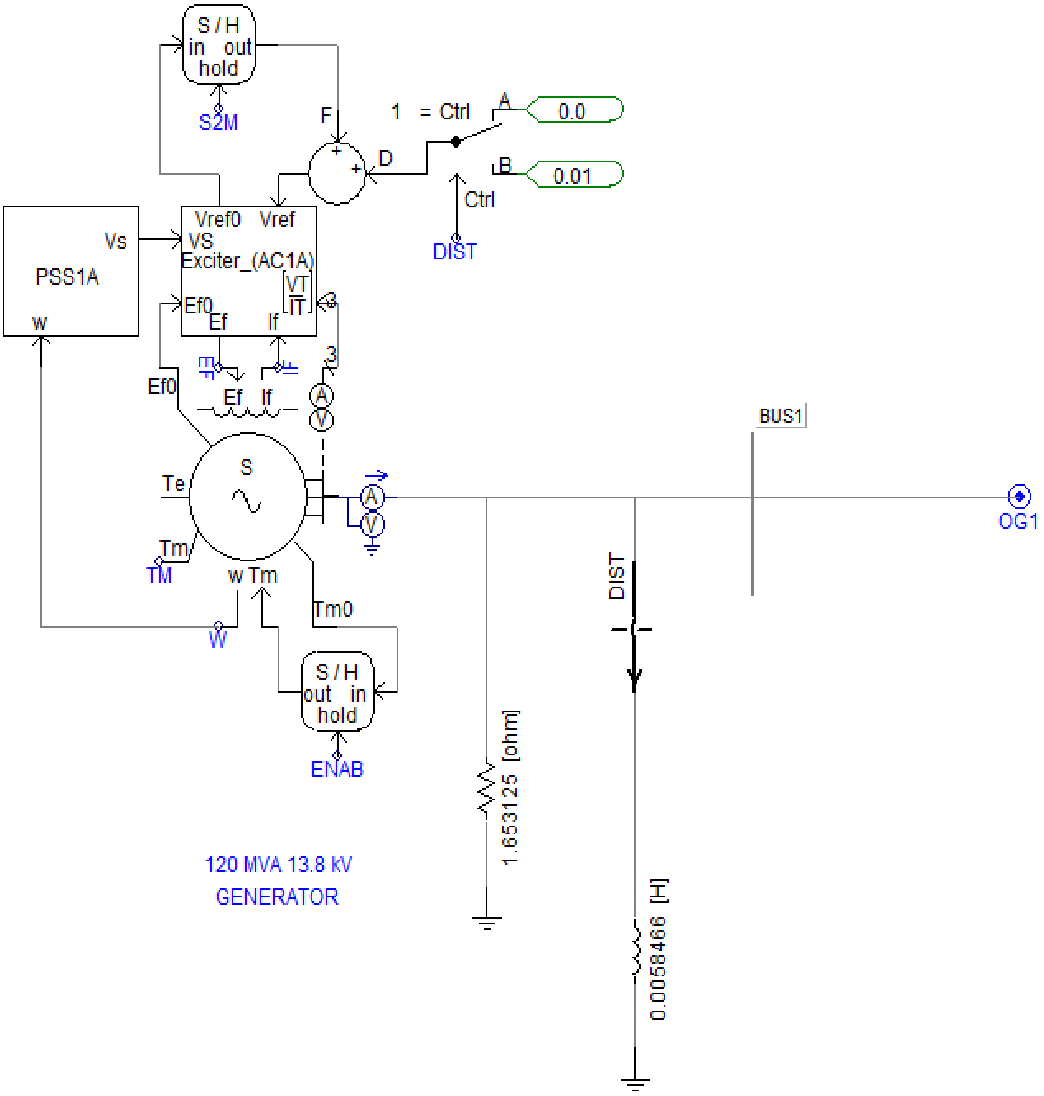


Figure 5.33 (b) PSCAD/EMTDC model of generator

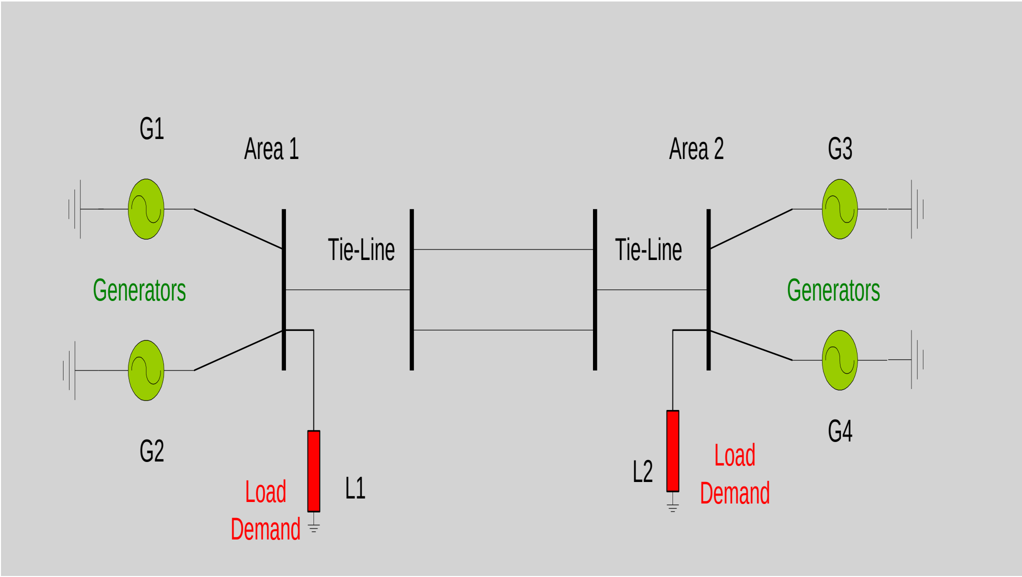


Figure 5.34 Two Area Four Machine test system

PSS Controller parameter up-gradation:

Case: 5.16

1) Initially Tuned PSS Controller: Loading in Area 1: PL(0+)=96MW QL(3+)=72MVar (i.e. R(0+)=1.98375; X(3+)=0.00701608) (**PSS Parameters:** T1=0.2400; T2=0.0010; T3=0.06; T4=0.01; Kc=15.0; Tw=10.0)
2) Retuned PSS as Load Increases 20 percentage: PL(0+)=96+20%MW; QL(3+)=72+20%MVar R(0+)=1.653125; X(3+)=0.0058466 (**PSS Parameters:** T1=0.3200; T2=0.0010; T3=0.06; T4=0.01; Kc=15.0; Tw=10.0)

System response shows effectiveness of retuning PSS parameters as load increases up to 20% from the nominal value. Two curves are shown in Figure 5.35 for each electrical quantity; one is for the initially tuned PSS controller as load changes and other is for the retuned PSS controller as operational shift occurs in the system. The same response has been shown in Figure 3.36 for generator 2 connected in area 1. The similarly behavior have been observed for all the generators connected in area 2.

Figures 5.35-5.38 show the electrical quantities of all four generators connected in the system with case 5.16. Retuning of PSS controllers increases the damping in system as compared to the initially tuned PSS parameter as the operational shift occurs in system. The same has been observed with state space modeling of two area system developed in MATLAB. Figures 5.39-5.42 show the perturbed response of all states variables for two area four machine test system for the same case study (Case 5.16) in the MATLAB software.

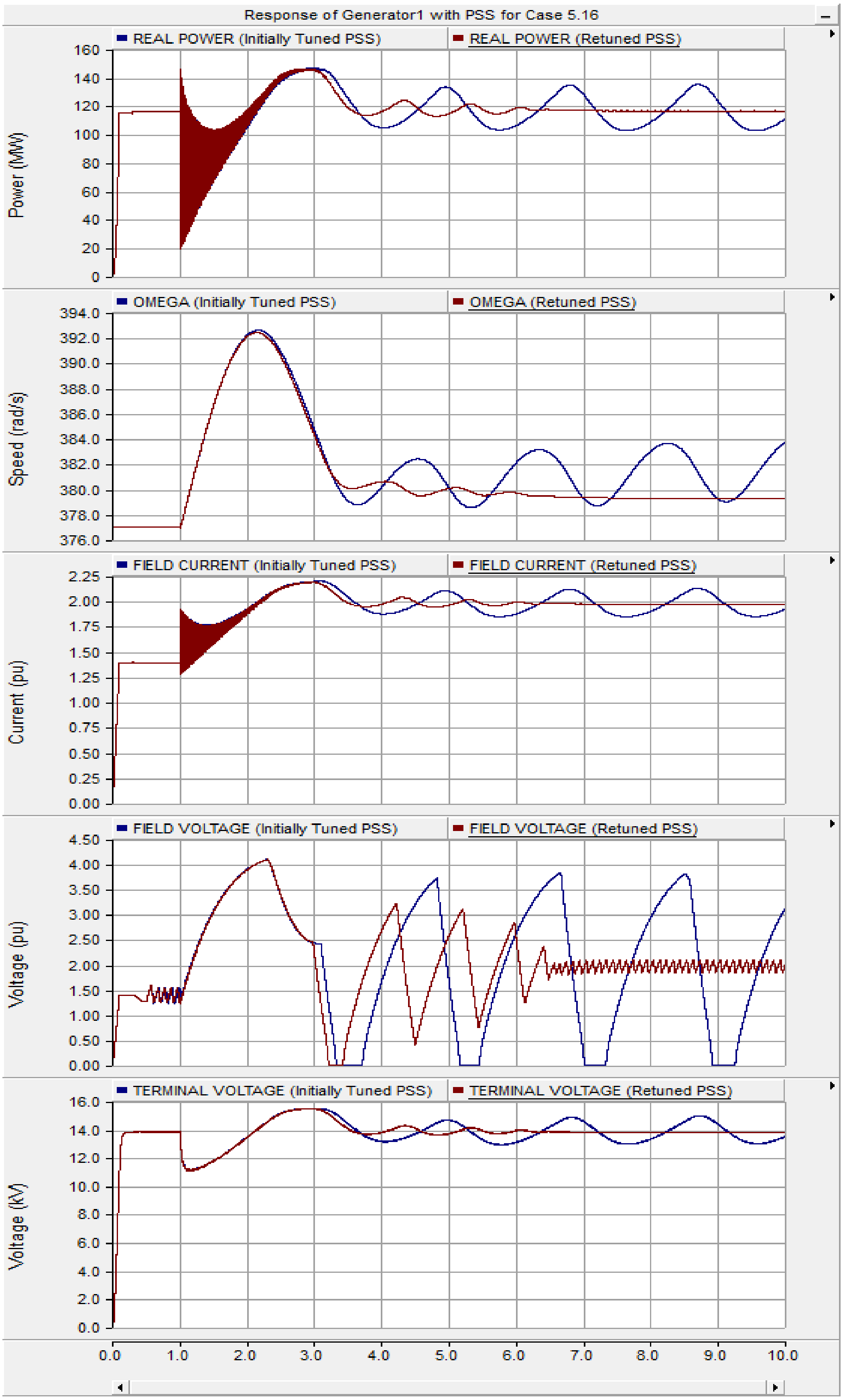


Figure 5.35 System response of generator 1 with case 5.16 (PSCAD/EMTDC)

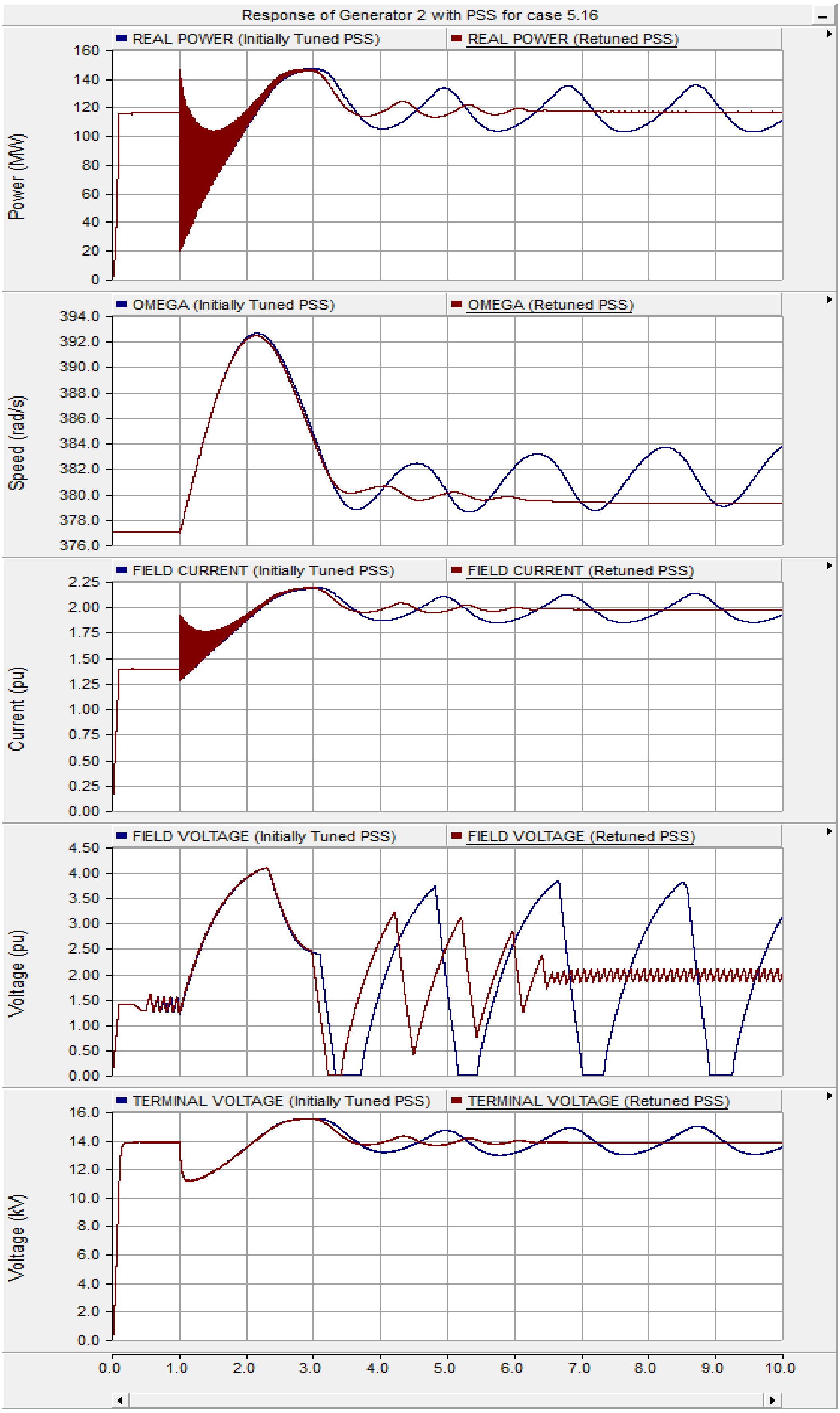


Figure 5.36 System response of generator 2 with case 5.16 (PSCAD/EMTDC)

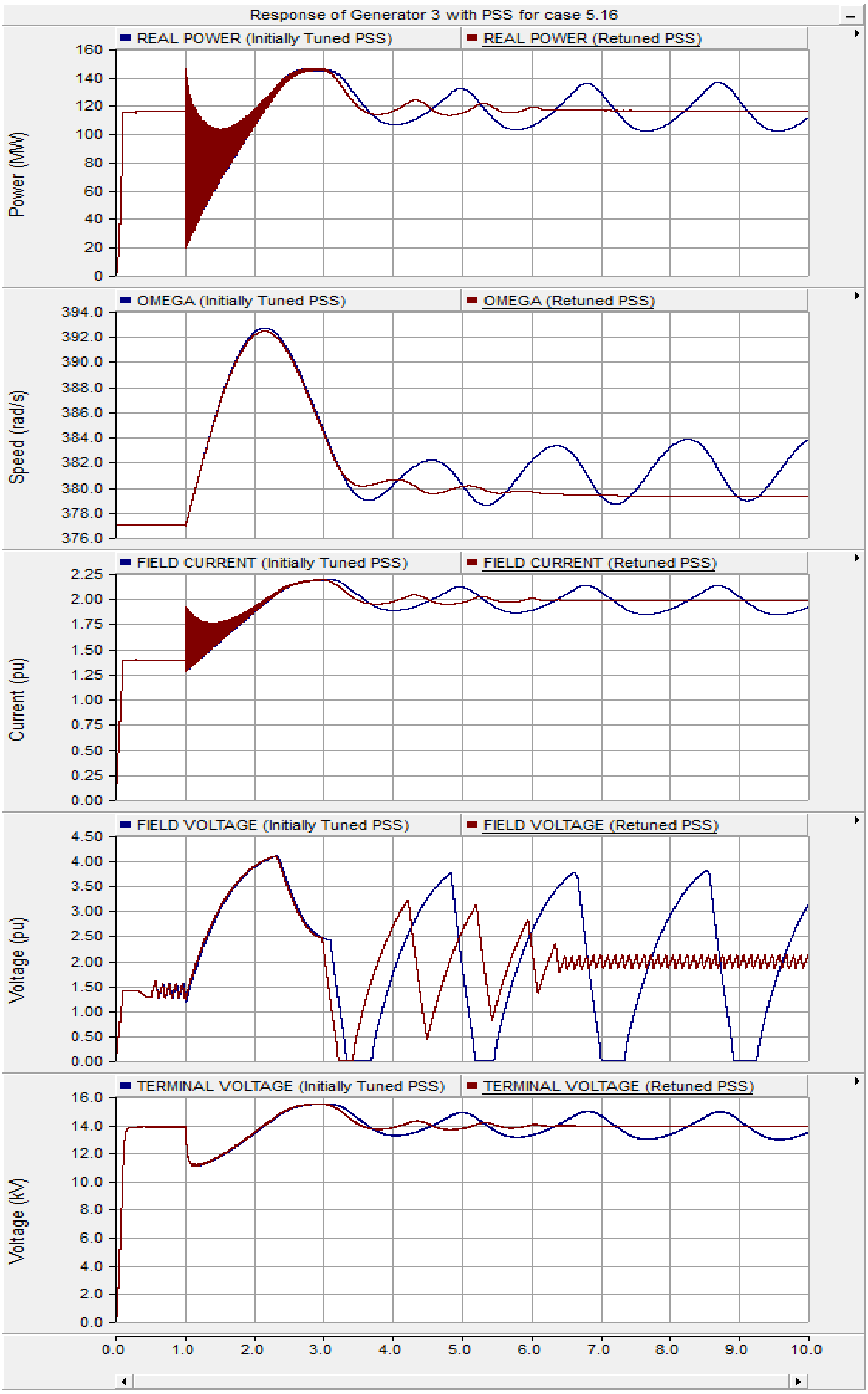


Figure 5.37 System response of generator 3 with case 5.16 (PSCAD/EMTDC)

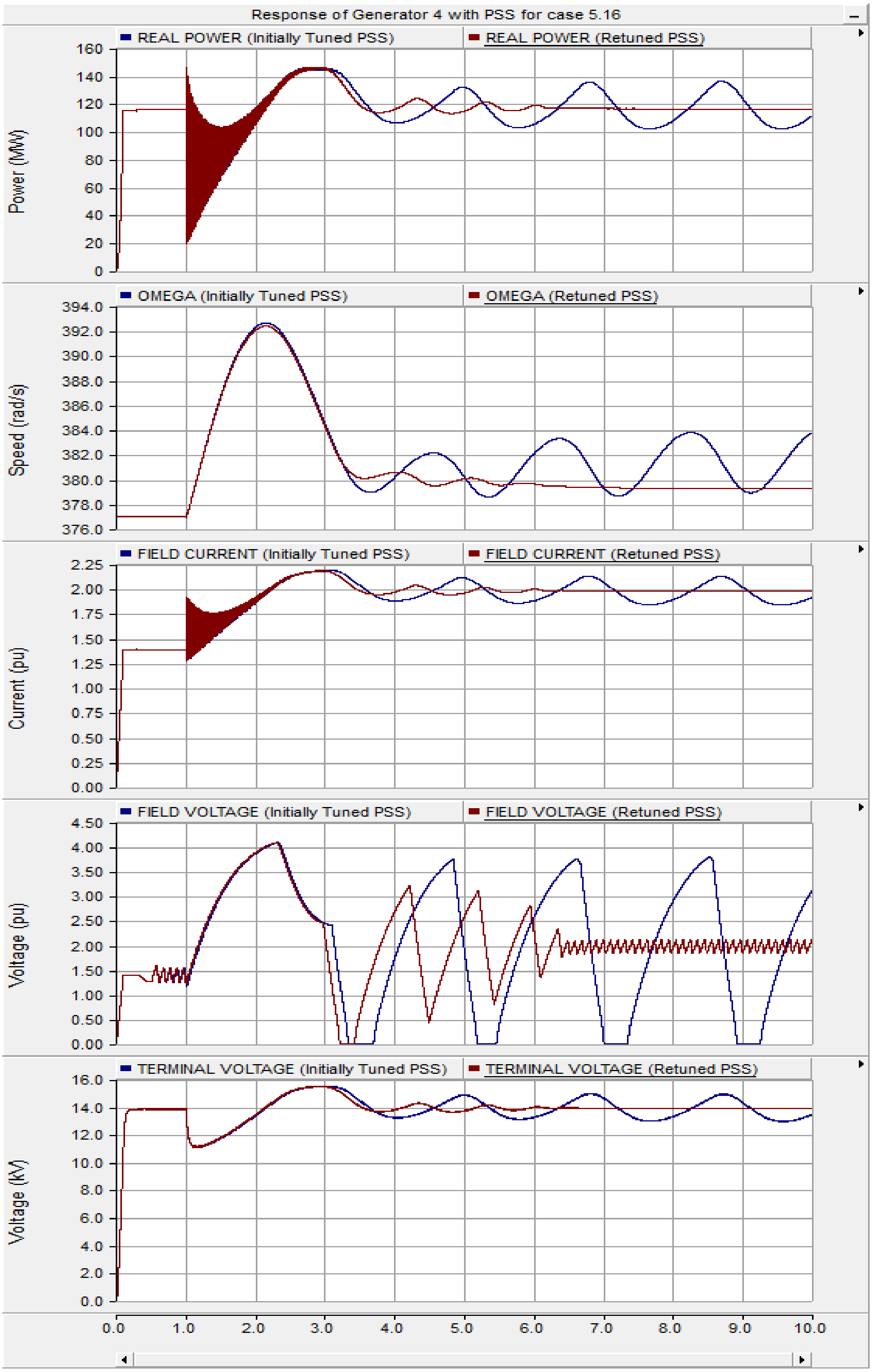


Figure 5.38 System Response of generator 4 with case 5.16 (PSCAD/EMTDC)

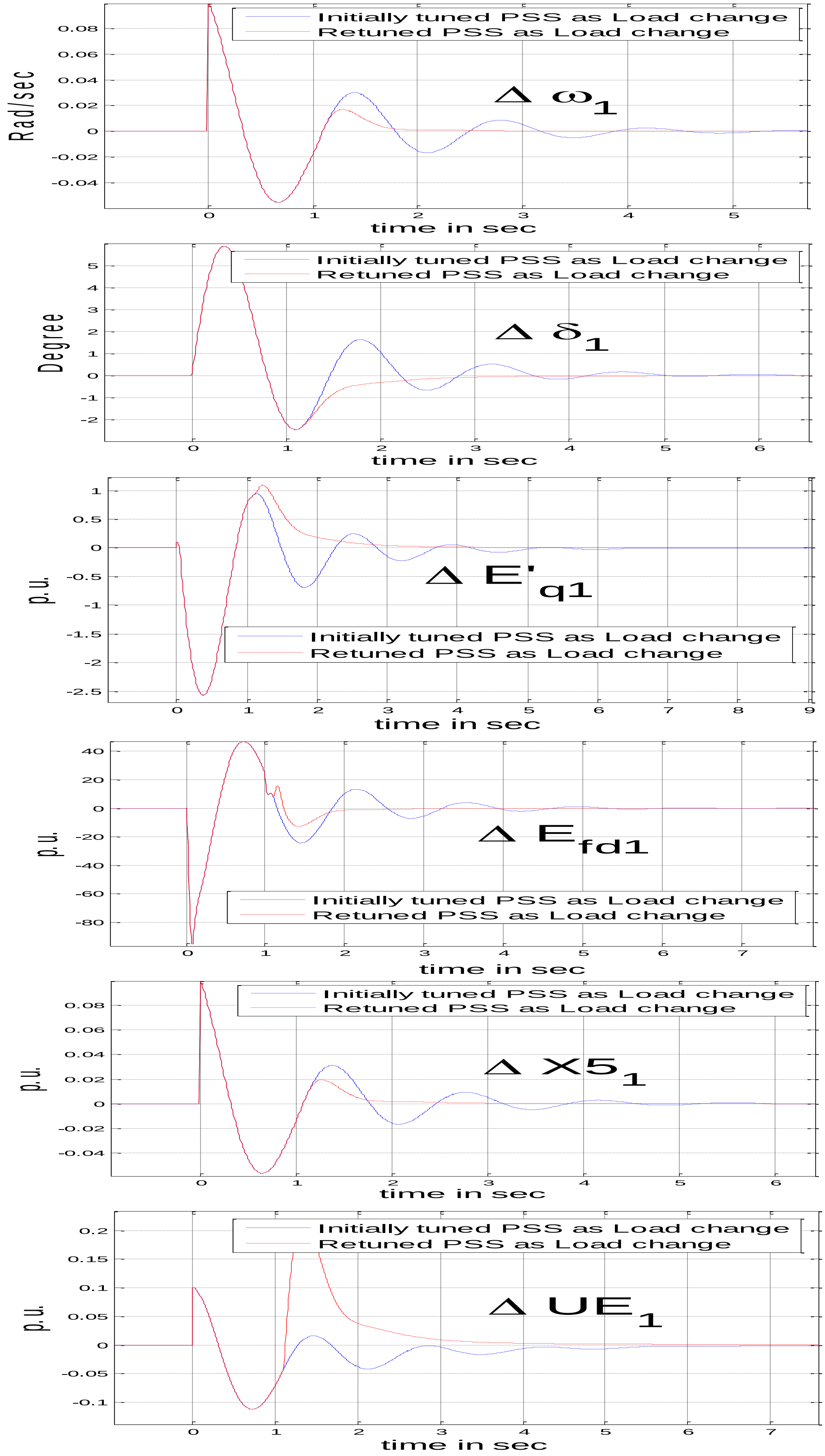


Figure 5.39 Perturbation response of generator 1 with case 5.16 (MATLAB)

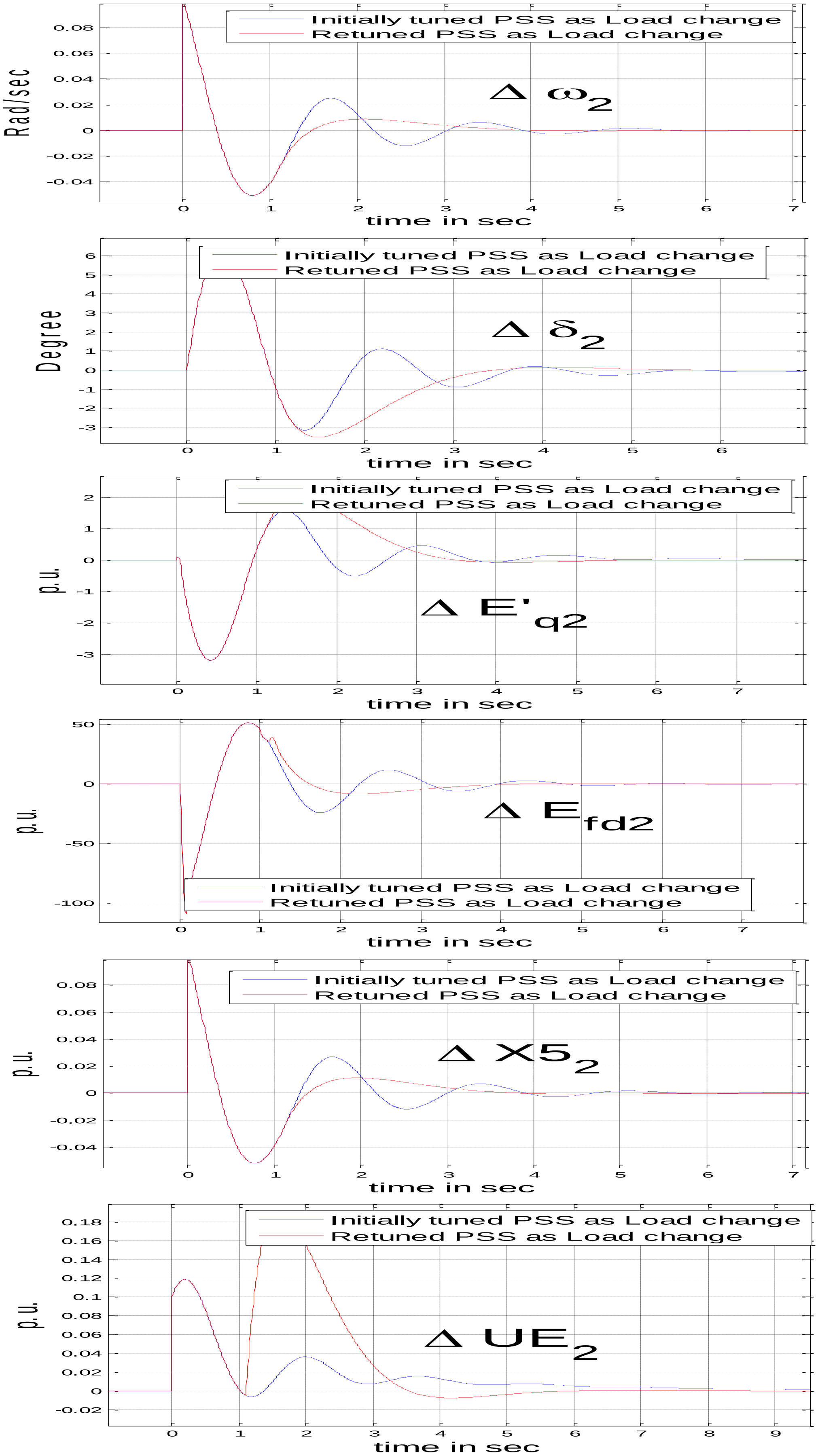


Figure 5.40 Perturbation response of generator 2 with case 5.16 (MATLAB)

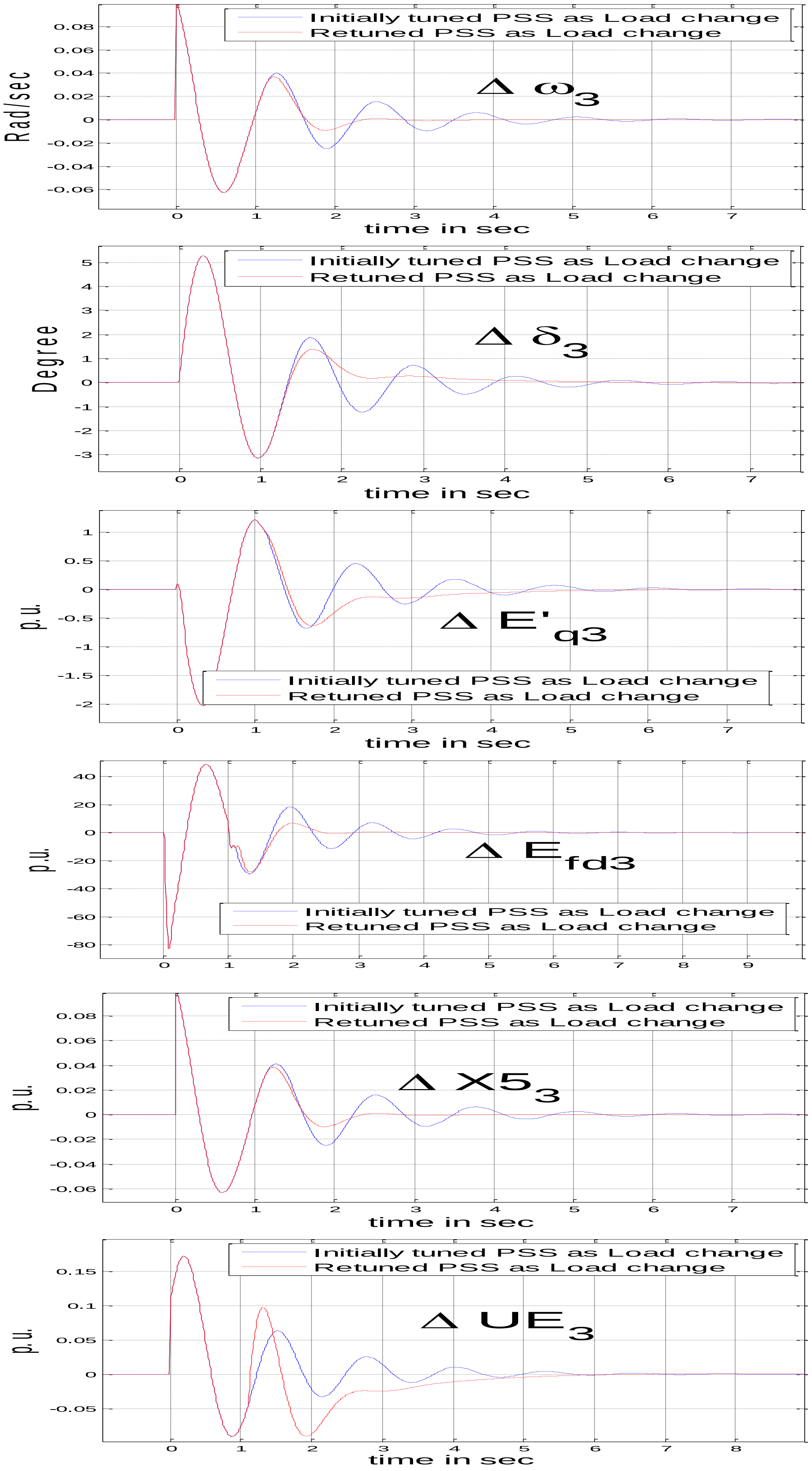


Figure 5.41 Perturbation response of generator 3 with case 5.16 (MATLAB)

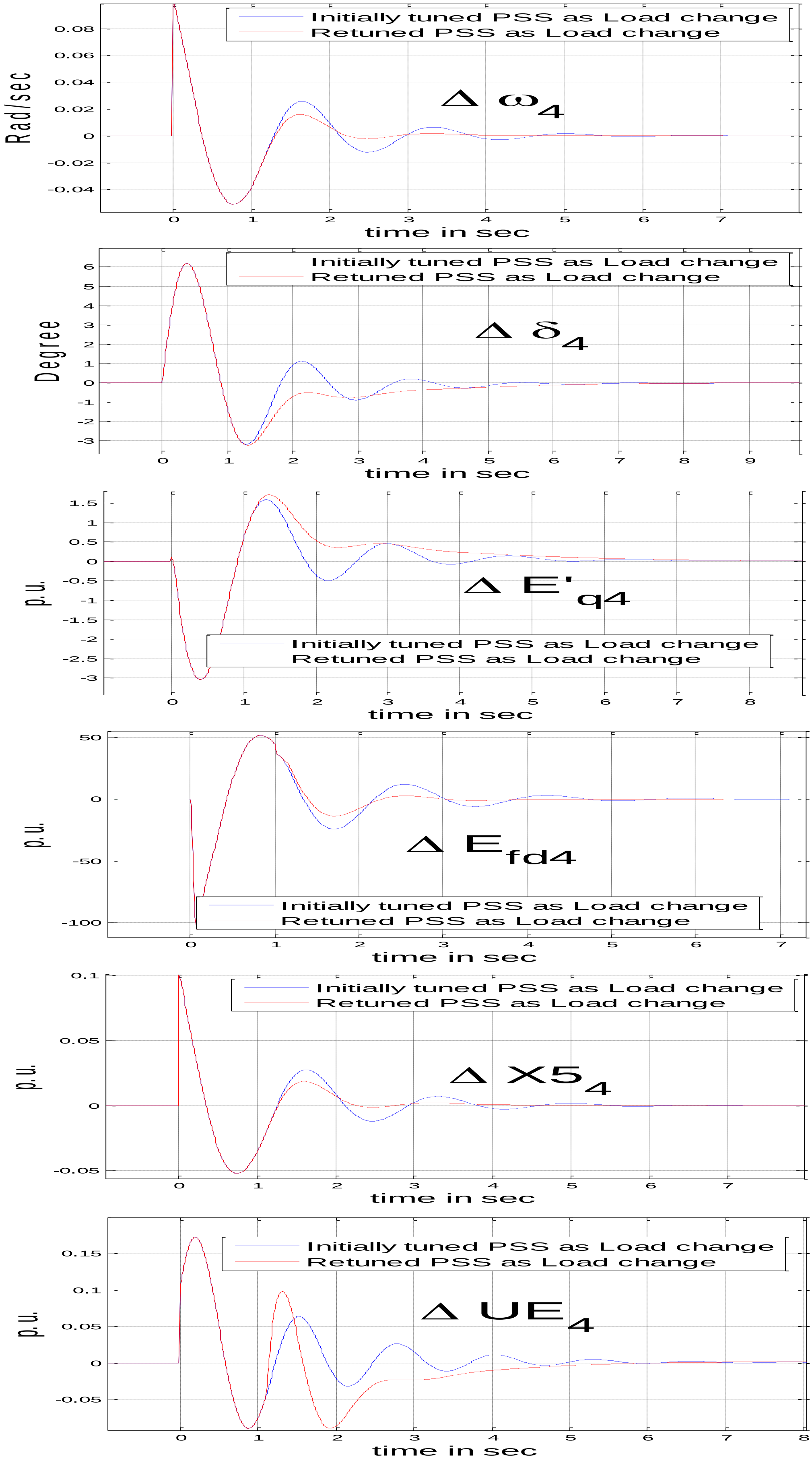


Figure 5.42 Perturbation response of generator 4 with case 5.16 (MATLAB)

FACTS Supplements PSS Controllers:

STATCOM has been used as supplementary controller after PSS tends to fail as the operating conditions in the system changes and goes beyond the range of local control to handle the extra perturbation. Case study has been developed where PSS approaches to the onset of unacceptable response and STATCOM act as supplementary control to stabilize the system.

Case Study: 5.17

PL(0+)=96+50% MW; QL(3+)=72+50%MVar

R(0+)=1.3225; X(3+)=0.004679 in Area 1

Here, PL = Real power loading in area 1, QL=Reactive power loading in area 1, R and X are per unit resistance and reactance loading respectively in each area.

With the increase of load in area 1 by 50%, response of generator 1 approaches to the unacceptable behavior as only PSS is supposed to handle extra perturbation. In this situation, control sharing concept enhances the damping in system with STATCOM sharing extra burden and thus assisting PSS as a supplementary controller. Figure 5.43 represents the PSCAD model of two area four machine system with STATCOM connected to bus 3. Detailed simulation modeling of STATCOM in PSCAD has been given in Figure 5.44. Generator response shows the effectiveness of control sharing concept as PSS tend to reach its maximum capacity to handle extra perturbation in the system and STATCOM supplements the PSS by handling extra perturbation and thus stabilizes system. Figure 5.45 shows the response of generator 1 with PSS alone and STATCOM supplementing PSS to stabilize the system. Similarly, the same behavior of all the controllers responses have been observed in area 2. The same has been observed with state space modeling of two area four machine test system developed in

MATLAB. Figures 5.46-5.47 show the perturbed response of all state variables of generator 1 for case 5.17.

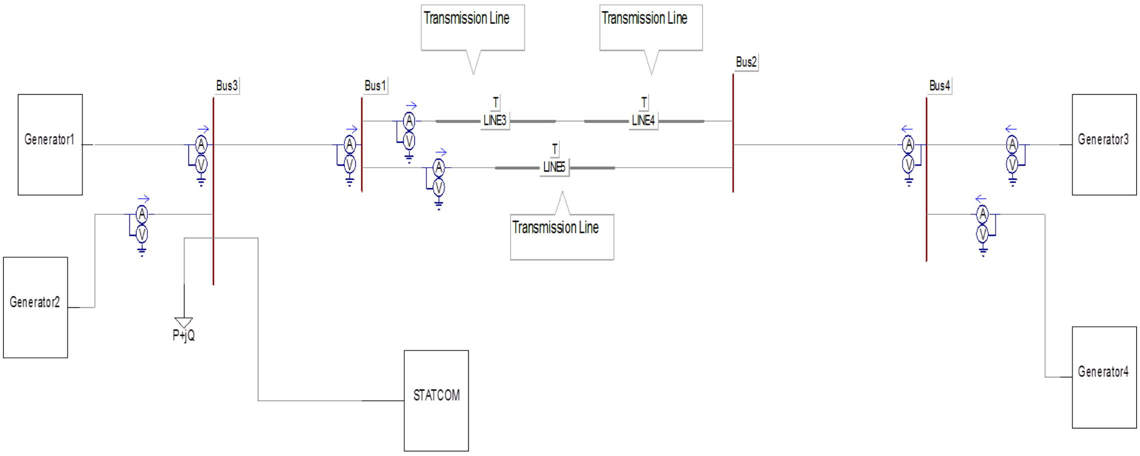


Figure 5.43 PSCAD model for Two Area Four Machine test system with STATCOM

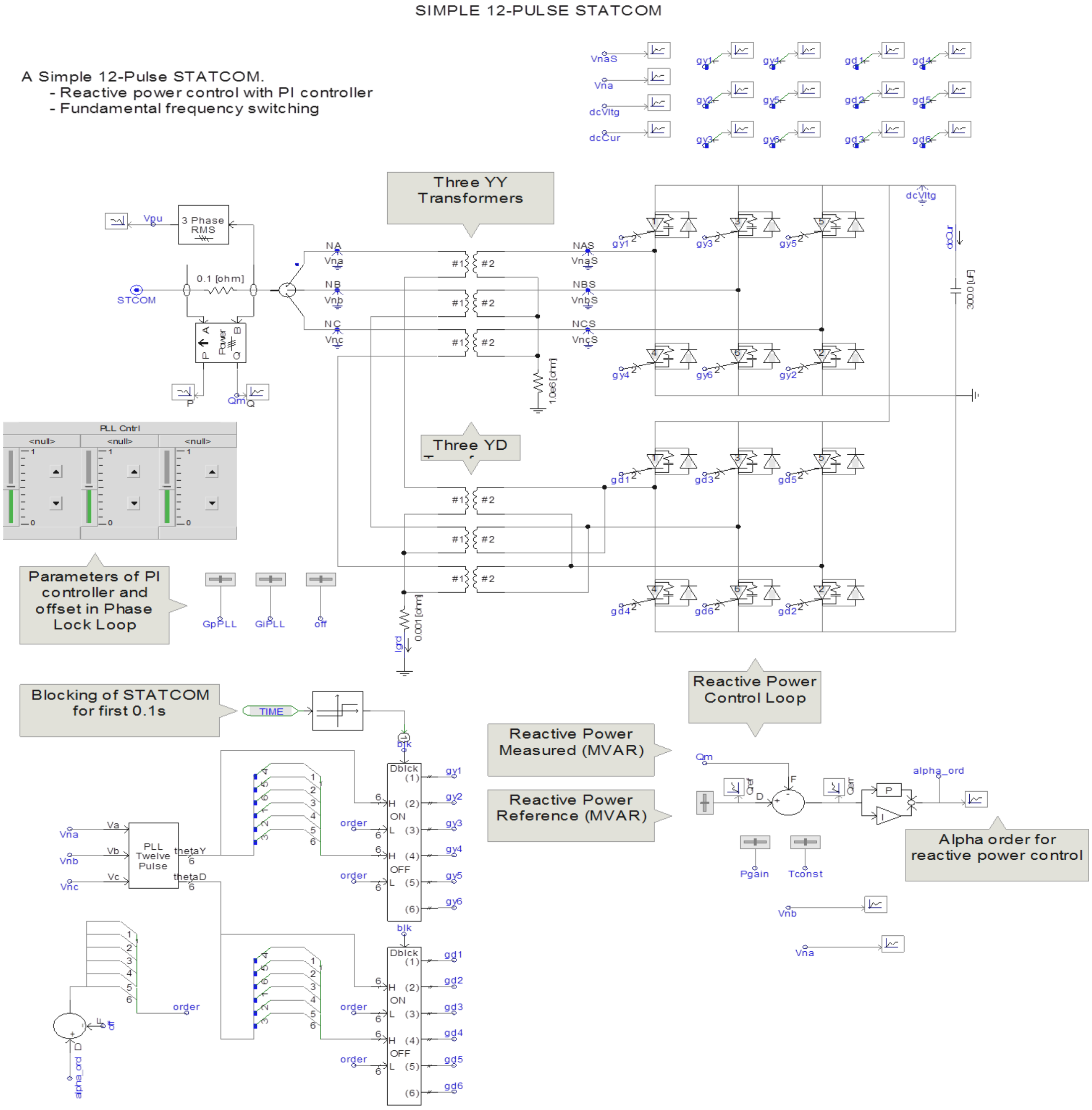


Figure 5.44 PSCAD model of STATCOM device

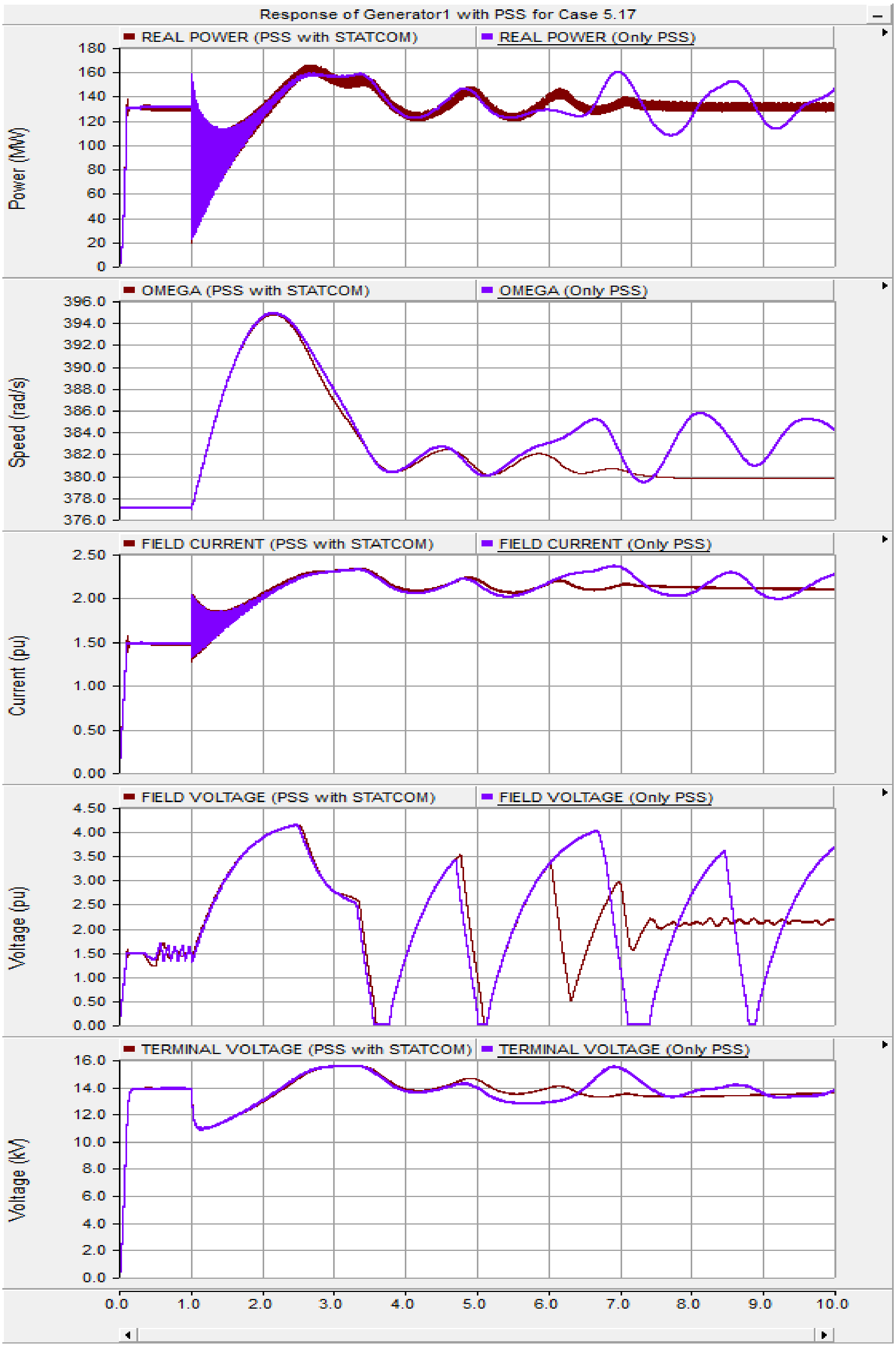


Figure 5.45 System response with the effect of STATCOM in addition to PSS for generator 1 with Case Study 5.17 (PSCAD Software)

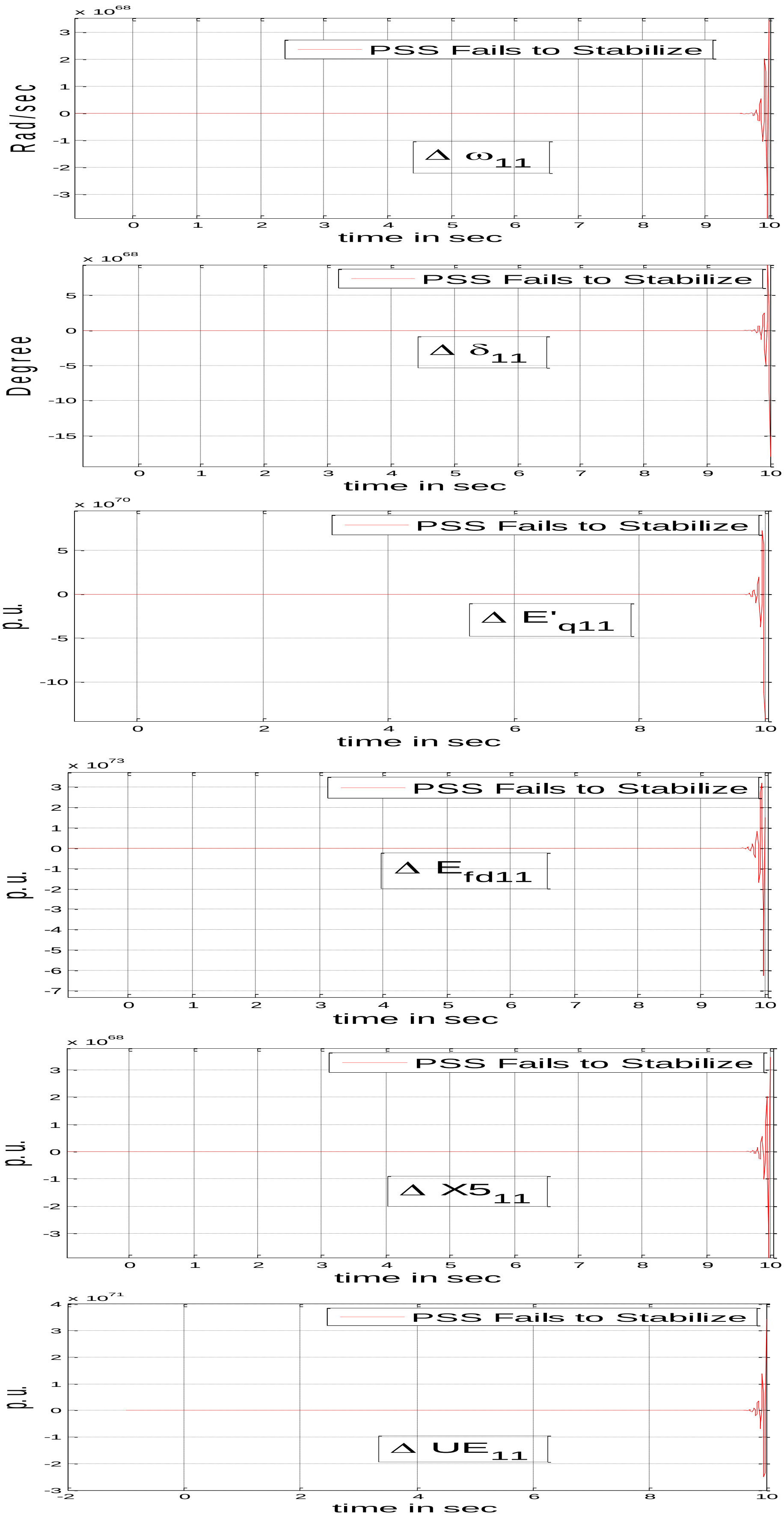


Figure 5.46 System response of generator 1 only with PSS (when PSS alone fails to stabilize the system) Case 5.17 in MATLAB Software

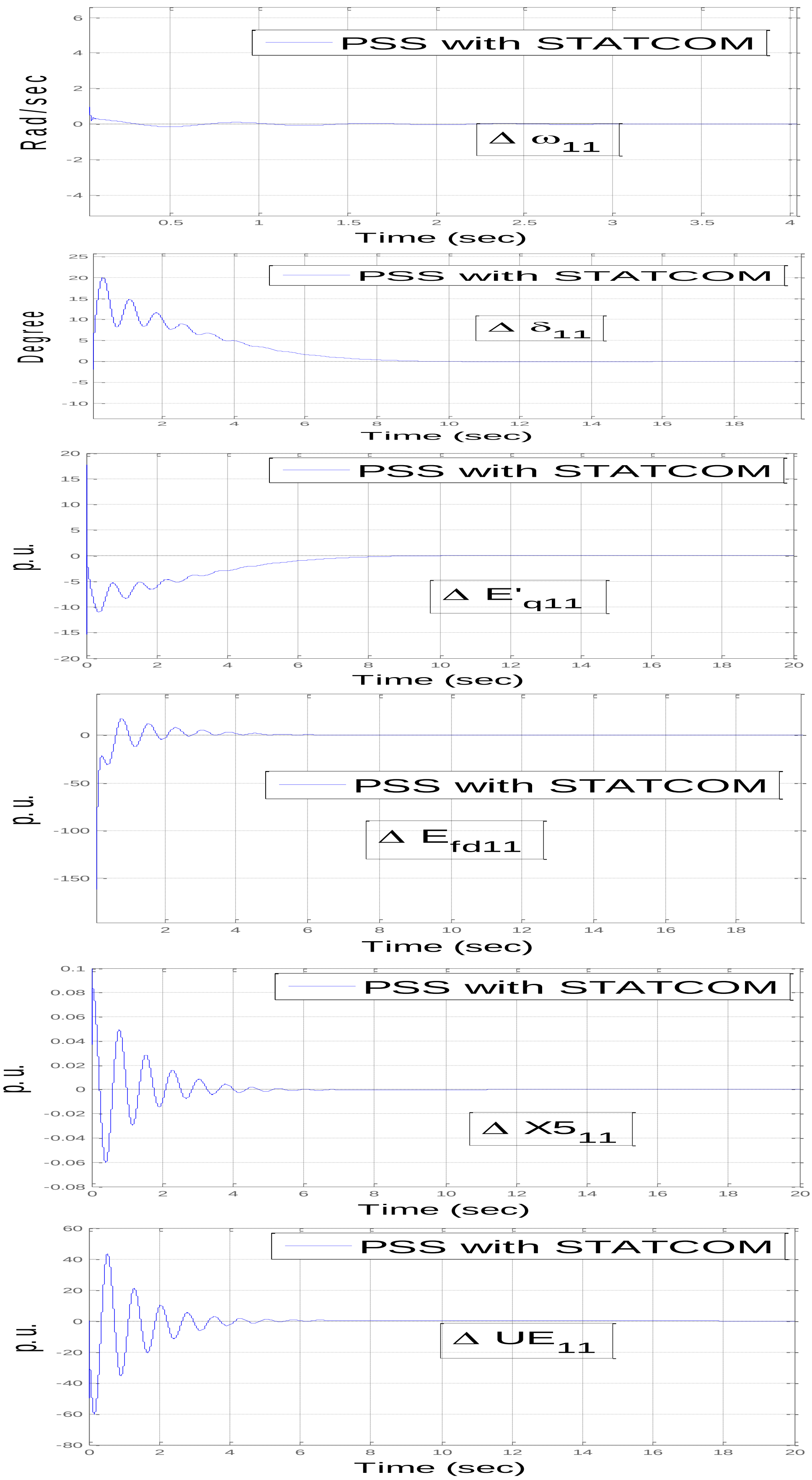


Figure 5.47 System response of generator 1 when STATCOM supplements PSS - Case 5.17 (MATLAB Software)

Figures 5.46-5.47 show the perturbation response of generator 1 of two area four machine test system. There are some differences between PSCAD and MATLAB simulation results in terms of oscillation of all the variables. This is due to the modeling procedure of PSCAD and MATLAB are different. Modeling in MATLAB based on the small signal modeling however PSCAD modeling is based on the detailed modeling of the entire system. Initially PSS tries to respond the variation in system loading by changing its control parameters with the use of knowledge inference mechanism; however when the perturbation goes beyond the range of PSS, STATCOM connected nearby modulate the power flow in system and thus stabilize all states variables as shown in Figure 5.47. The results present complete hierarchy of control structure for all the controllers connected in system. Initially local controller (like PSS) tries to address perturbation in system, however when local controller approaches to the onset of unacceptable behavior for specific system operating conditions another controller (may be FACTS devices) deployed in the network act as supplementary controller, in addition to the existing controller and helps to restore the system by modulating required real and reactive power flow in the system.

5.3 CONCLUSION

This chapter demonstrates the effectiveness of proposed concept of knowledge domain states mapping concept for intelligent power oscillation damping of multi-area system. System studies have been extensively carried out for various operational shifts. The model developed has been effectively used to simulate all possible conditions which demonstrate the effectiveness of proposed concept of knowledge domain states mapping for intelligent power flow control. A rigorous system study has been done under variety of dynamical changes, the controller tuning by all heuristic approaches mentioned in Chapter 4 has been done and results demonstrate the best system response and appropriate tuning method. The overall system considered has been subjected to on-going perturbation along with associated control strategy such as PSS alone and also coordination of PSS with FACTS devices. The results with such controller structure demonstrate the concept of intelligent power control concept under variety of operational conditions. The concept of intelligent controller (hierarchical control structure) augmentation such as parametric range extension and controller sharing and shifting has been extensively studied for large system. The main aspect of this concept is control parameter's up-gradation and control shifting/sharing concept. Various case studies with different test systems have been shown to increase the system stability with hierarchical control structure. Validation of the proposed concept with professional PSCAD/EMTDC software has also been reported in this chapter.