An Intelligent Coordinated design of UPFC based Power System Stabilizer for dynamic stability enhancement of SMIB Power System

[1]Bagepalli Sreenivas Theja, [2]Anguluri Rajasekhar
Department of Electrical and Electronics Engineering
National Institute of Technology-Warangal, INDIA
[1]sreenivastheja11972@gmail.com,
[2]rajasekhar.anguluri@ieee.org

[3]Prof D.P. Kothari, *Fellow-IEEE*,
[3]Director General, Raisoni group of Institutions
Nagpur, 440001 INDIA
[3]dpk0710@yahoo.com

***Abstract*— In this paper an optimal coordinated tuned UPFC controller has been proposed to enhance the damping of low frequency oscillations in a single machine infinite bus power system. The design of controller is developed as optimization model and it is carried out using a novel Elitist Teaching Learning Opposition based algorithm (ETLOBA).**

Keywords:, PSS, SMIB, ETLOBA, UPFC, small signal stability

I. INTRODUCTION

Now-a-days, due to the rapid rise in the power demand heavy loads are being imposed on modern day power systems. This leads the power systems to operate near their transient stability limits. To achieve the better reliability of power supply, the continuous balance between the electrical power generated and varying load demand is essential [1, 2, 5, 6].

In order to maintain the distantly located interconnected power systems at constant operating voltage, fast acting high gain Automatic Voltage Regulators (AVR) are being used for synchronous generators. AVRs cause negative damping on the rotor. This eventually leads to small frequency oscillations (0.1-3 Hz) which may affect the small signal stability (ability to maintain synchronism under small disturbances and changes in generation and loads. To overcome this unwanted effect Power System Stabilizers are being employed. The major role of PSS is to produce positive damping on rotor oscillations by introducing additional supplementary signals in the feedback loop of voltage regulator [2, 5]. But PSS may not produce sufficient damping under some operating conditions. It causes variations in voltage profiles and has high operating time. The rapid advancements in the field of high power semiconductor technology lead to the provision of controlling electrical power systems with the help of Flexible AC Transmission Systems (FACTS) devices. Owing to their fast operation, they have been economically useful for enhancement of power transfer capability and power system stability. Unified Power Flow Controller belongs to the family of second generation FACTS devices. It has the ability to adjust the three control parameters, i.e. the bus voltage, transmission line reactance and phase angle between two buses, either simultaneously or independently to control power flow and improve the stability. It can also improve the small signal stability by the damping of low frequency power system oscillations. A UPFC performs this through the control of in-phase voltage, quadrature voltage and shunt compensation [1, 3, 4, 7]. Wang has proposed a modified linear Philip-heffron's model of a power system equipped with UPFC [3]. He had demonstrated the issues related to the design of damping controller and choice of parameters of UPFC (m_B, m_E, δ_B, δ_E) to be modulated to achieve desired damping. To obtain parametric values of various UPFC controllers, trial and error methods are not suitable [10] and also to avoid the destabilizing interactions the tuning of parameters of different controllers should be coordinated. As the coordinated approach is more intricate than normal controller design and efficient algorithm should be developed to get optimal parametric values for UPFC controller such that stability is attainted with less settling time. For, this purpose we propose a new ELTOBA algorithm a variant of Teaching Learning based optimization (TLBO) algorithm which includes the concept of elitism and opposition based learning. The rest of the paper is organized as follows; Section 2 deals with the mathematical modeling of power system for single machine infinite bus system with UPFC controller. In Section 3 the problem is formulated followed by the objective function considered. Section 4 briefs the ETLOBA algorithm and design scheme is been provided in Section 5. The simulations and results are put forth in Section 6 and at end we provide few conclusions.

II. POWER SYSTEM MODELING

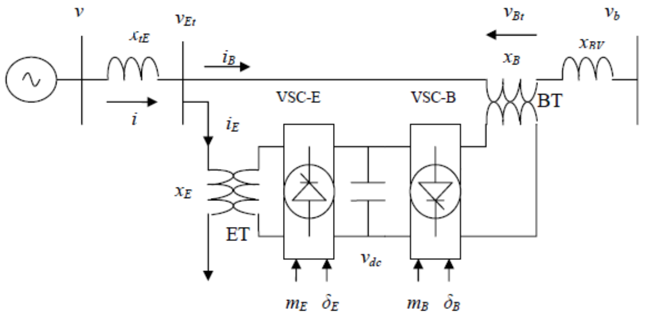

Fig.1 Single machine infinite bus power system with UPFC [1]

A SMIB power system model equipped with UPFC shown in Fig.1 is used to obtain linearized modified Philip-Heffron's model with UPFC. The dynamic modeling of components in the power system like synchronous generator, excitation system, AVR, UPFC etc. is needed for small signal stability studies.

A. Unified Power Flow Controller (UPFC)

The UPFC consists of a shunt connected excitation transformer (ET), series connected boosting transformer (BT), two three-phase Gate Turn Off (GTO) based voltage source converters (VSCs) and a common DC link capacitors. The four input control signals to the UPFC are modulation index of shunt converter (m_E), phase angle of the shunt-converter voltage (δ_E), modulation index of series converter (m_B) and phase angle of injected voltage (δ_B) [7].

Two voltage converters VSC-E and VSC-B are operated from a common DC link provided by a DC storage capacitor. The primary function of shunt converter is to supply the real power demand to the series converter. It also regulates the terminal voltage of the interconnected bus by controlling the reactive power supply to that bus. The series converter is controlled to inject a voltage V_{Bt} in series with the line and its magnitude can be varied from 0 to $V_{Bt,max}$ and its phase angle can be varied independently from 0 to 360^0. A DC voltage regulator is provided to maintain real power balance between two voltage converters. DC voltage is regulated through modulating the phase angle of shunt converter voltage (δ_E). Equation for real power balance between series and shunt converters is given as

$$\mathrm{Re}\ (V_{Et} i_E^* - V_{Bt} i_B^*) = 0$$

B. Nonlinear dynamic model

The generator is represented by the 3^{rd} order consisting of the swing equation and the generator internal voltage equation. The resistances of all the components of the system and transients of the transmission lines are neglected while deriving the algebraic equations. IEEE –ST1type excitation system is considered. The nonlinear model of SMIB system with UPFC is given as below

$$\delta^{\bullet} = \omega_o(\omega - 1) \qquad (1)$$

$$\omega^{\bullet} = (P_m - P_e - D(\omega - 1))/M \qquad (2)$$

$$E'^{\bullet}_q = (E_{fd} - (x_d - x'_d)i_d - E'_q)/T'_{do} \qquad (3)$$

$$E^{\bullet}_{fd} = (K_A(V_{ref} - v + u_{pss}) - E_{fd})/T_A \qquad (4)$$

$$v^{\bullet}_{dc} = \frac{3m_E}{4C_{dc}}(i_{Ed}\cos\delta_E + i_{Eq}\sin\delta_E) + \frac{3m_B}{4C_{dc}}(i_{Bd}\cos\delta_B + i_{Bq}\sin\delta_B) \qquad (5)$$

$$v = v_d + jv_q = x_q(i_{Eq} + i_{Bq}) + j[E'_q - x'_d(i_{Ed} + i_{Bd})] \qquad (6)$$

$$P_e = v_d i_d + v_q i_q \qquad (7)$$

Detailed nonlinear model can be found in [1].

C. Linear dynamic model

The linear dynamic model is obtained by linearizing the nonlinear differential equations around an operating condition. The linear dynamic model is given as below

$$\Delta P_e = K_1\Delta\delta + K_2\Delta E'_q + K_{pd}\Delta v_{dc} + K_{pe}\Delta m_E + K_{p\delta e}\Delta\delta_E + K_{pb}\Delta m_B + K_{p\delta b}\Delta\delta_B \qquad (8)$$

$$\Delta E'^{\bullet}_q = \frac{1}{T'_{do}}[\Delta E_{fd} - (K_4\Delta\delta + K_3\Delta E'_q + K_{qd}\Delta v_{dc} + K_{qe}\Delta m_E + K_{q\delta e}\Delta\delta_E + K_{qb}\Delta m_B + K_{q\delta b}\Delta\delta_B)] \qquad (9)$$

$$\Delta v = K_5\Delta\delta + K_6\Delta E'_q + K_{vd}\Delta v_{dc} + K_{ve}\Delta m_E + K_{v\delta e}\Delta\delta_E + K_{vb}\Delta m_B + K_{v\delta b}\Delta\delta_B \qquad (10)$$

$$\Delta v^{\bullet}_{dc} = K_7\Delta\delta + K_8\Delta E'_q - K_9\Delta v_{dc} + K_{ce}\Delta m_E + K_{c\delta e}\Delta\delta_E + K_{cb}\Delta m_B + K_{c\delta b}\Delta\delta_B \qquad (11)$$

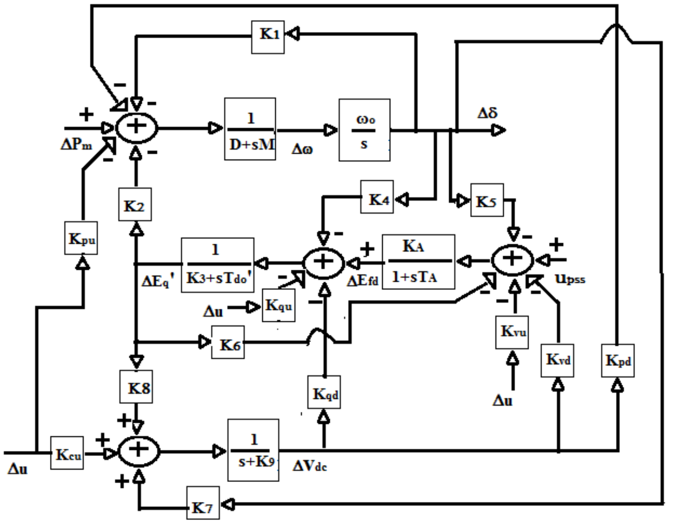

Fig.2 Linear Philip-Heffron model of SMIB power system with UPFC

D. Excitation system and PSS

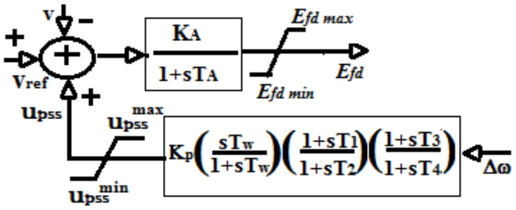

Fig.3 IEEE type - ST1 excitation system with PSS

The conventional two stage lead-lag power system with IEEE-ST1 type excitation system is considered. For the excitation system inputs are terminal voltage (V_T), supplementary signal (V_s) from PSS and reference voltage (V_{ref}). K_A and T_A are the gain and time constant of excitation respectively. The PSS takes the speed deviation signal (Δω) as input to produce a component of electrical torque in the direction of Δω and gives a supplementary control signal

(ΔV_s) to excitation system as output. A schematic representation is presented in Fig 3. of PSS along with excitation.

E. UPFC Damping controllers

The lead-lag damping controllers are designed to produce a component of electrical torque in the direction of speed deviation to produce sufficient positive damping in order to provide damping on small frequency power system oscillations. The four control parameters (m_B, m_E, δ_B, δ_E) are modulated to produce sufficient damping. The parameter m_B controls the magnitude of series voltage injected, there by controls the reactive power compensation. By varying the parameter δ_B the real power flow can be controlled. The parameter m_E can be modulated to control the voltage at the bus where UPFC is installed. The damping controllers for m_B, m_E, δ_B are as shown below, where 'u' may be any of the m_B, m_E, δ_B.

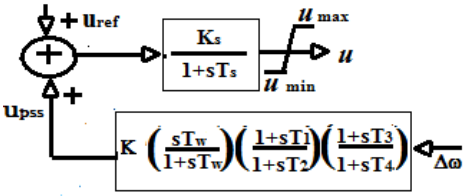

Fig.4 Structure of Lead-lag UPFC controller (m_B, m_E, δ_B)

The parameter δ_E can be modulated to regulate the DC voltage at DC link. So, the δ_E damping controller as shown below is provided with a *PI* controller, which functions as DC voltage regulator

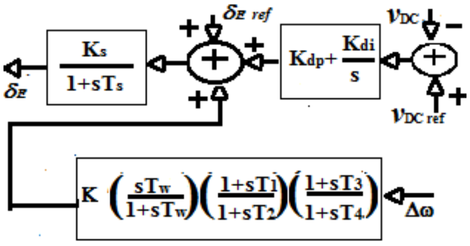

Fig.5 Structure of δ_E Lead-lag controller with DC voltage regulator

III. PROBLEM FORMULATION

A. Structure of UPFC Damping controllers

The conventional lead–lag structure is chosen for UPFC damping controllers in this study. It consists of a gain block with gain K, a signal washout block and two-stage phase compensation block as shown in fig. 4 and 5. The phase compensation block provides the appropriate phase-lead characteristics to compensate for the phase lag between input and the output signals. The signal washout block serves as a high-pass filter, with the time constant T_W (5 sec), high enough to allow signals associated with oscillations in input signal to pass unchanged.

In this design T_W is usually pre-specified. The gains K and T_1, T_2, T_3, T_4 are to be determined. The input signal of the proposed damping controllers is the speed deviation ($\Delta\omega$) and the output is supplementary signal is u (m_B, m_E, δ_B, δ_E).

B. Objective function

The performance of the system considered depends on the controller parameters, which in turn depends on the objective function to be minimized. The design of damping is done based on minimizing the objective function considered in order to reduce the power system oscillations after a disturbance in loading condition so as to improve the stability of power system. In this paper the objective function is formulated in such a way that rotor speed deviation is minimized and is mathematically formulated as follows

$$J = \sum \int_0^t t[\Delta\omega(t, X)]^2 \, \mathrm{d}t \qquad (17)$$

In the Eqn. (17), $\Delta\omega(t, X)$ denotes the rotor speed deviation for a set of controller parameters X. Here X represents the parameters to be optimized. The optimization is carried in two phases, initially the 5 parameters corresponding to each of the two individual controllers considered in each case are been tuned and in second phase coordinated tuning of total 10 parameters corresponding to both controllers considered is carried out. In the case of nominal and heavy loading conditions SMIB system with m_E, δ_B controllers have shown relatively lower stability than that of system without UPFC (only PSS). So, in the case of nominal and heavy loading conditions only m_B, δ_E controllers are considered for tuning. In the case of light loading condition SMIB system with m_E, δ_E controllers have shown relatively lesser stability than that of system without UPFC (only PSS). So, in the case of nominal and heavy loading conditions only m_B, δ_B controllers are considered for tuning.

IV. PROPOSED ALGORITHM: ETLOBA

A. Teaching Learning Based Optimization

Teaching Learning based optimization (TLBO) is a new metaheuristic proposed by Rao et al [8] for solving mechanical design problems and soon it has been used for solving various engineering problems. Inspired by this method we propose a new scheme to enhane the capability of TLBO and we term it as ETLOBA. The basic steps invovled in TLBO are summarized below

[step1] Initialize the population within the search space and also the termination criterion.

Teacher phase

[step2] Calculate the mean in each dimension.

[step3] The best minimial solution from the population is assigned to teacher

[step4] Each learner is updaed based on the teacher and the teaching factor (T_F)

[step5] If the newly obtained solution is better than the previous one, then the position of the learner is changed to the new solution ore else it is retained.

Learner Phase

[step6] Select any one learner randomly and update each learner based on the reandomly selected learner.

[step7] If the newly obtained solution is better than the previous one, then the position of learner is changed to the new solution else retain.

[step8] Check for termination criterion. If termination is not reached, repeat steps from 2 to 8

[step9] After termination, obtain the global minimal value for the population, which is the required minimum value.

B. *Elitist Teaching Learning Oppostion Based Algorithm*

1) Elitism*:*

Elitism is a mechanism to preserve the best individuals from generation to generation. It had been widely used in the field of evolutionary algorithms to obtain the solution with less computational effort. In the TLBO algorithm after replacing the existing worst solutions with elite solutions at the end of learner phase, if the duplicate solutions exist then care is taken modify the duplicate solutions in order to avoid trapping in the local optima. Now after every learner phase best solutions are retained and the teacher is being updated with the best solution obtained so far. Once the elitism has been introduced now the algorithm has to be further strengthened via increasing the global exploration capabilities which is done by using Opposition based learning rule.

2) Opposition based optimization:

Let $P = \{x_1, x_2, ..., x_D\}$ be a point in *D*-dimensional space, where $x_1, x_2, ..., x_D \in R$ and $x_i \in [a_i, b_i]$ $\forall i \in \{1,2,...,D\}$. Now $P^{'} = \{x_1^{'}, x_2^{'}, ..., x_D^{'}\}$ i.e., opposite point $P^{'} = \{x_1^{'}, x_2^{'}, ..., x_D^{'}\}$ is defined as [9]

$$x_i^{'} = a_i + b_i - x_i$$

Now, with above definition of opposite point the opposition based optimization can be formulated as follows. Assuming $f(\cdot)$ is fitness function via which candidate fitness is measured and according to the above given definitions of P and $P^{'}$ if $f(P^{'}) \geq f(P)$ then the point P can be replaced with $P^{'}$; hence, the point and its opposite point are evaluated simultaneously in order to go with the fitter one. Parameters considered for tuning are as follows *learners* =10, No. of iterations=200, algorithm is repeated 10 times for calculation of mean and std. deviation.

V. DESIGN OF UPFC DAMPING CONTROLLERS

A. *Parameters of the power system considered*

For the small signal stability analysis of SMIB the design of the system and system data is taken from [1].

1. System data: All data are in p.u unless specified otherwise

2. Generator: H=4.0 s, D=0, X_d=1.0, X_q=0.8, $X_d^{'}$ =0.3, T_{d0}'=5.044, f=60p.u *v*=1.05

3. Exciter: (IEEE type ST1) K_A=50, T_A=0.05s, $E_{fd\,max}$=7.3 p.u & $E_{fd\,min}$= -7.3 p.u

4. Transformer and transmission line: = X_{tE}=0.1 and X_{BV}=0.6

5. PSS data: T_W=5;T_{i_min}=0.01;T_{i_max}=5.0 where i=1, 2, 3& 4

PSS output limits = ± 0.2

6. UPFC data: X_E=X_B=0.1 and m_B=0.0789, δ_B = -78.2174^0, m_E=0.4013, δ_E = -85.3478^0 m_B and m_E *output limits* = 0 to 1 K_s=1 and T_s=0.05

7. DC link: V_{DC}=2 p.u, C_{DC}=3 p.u

As the optimization is carried out within bounds the following ranges are considered for the parameters to be tuned. The parameters being considered for tuning were K, T_1, T_2, T_3, T_4. Maximum and minimum parameters considered are as follows 0.01< T_1, T_2, T_3, T_4 <5.0 and for different controllers indicated with sub scripts 0<K_{mB}<100 and -100< K_{mE}, $K_{\delta B}$, $K_{\delta E}$ <0.

VI. SIMULATIONS AND RESULTS

The loading conditions considered are Nominal loading (P_e=1.0 & Q_e=0.015), Light loading (P_e=0.3 & Q_e=0.015) and Heavy loading (P_e=1.1 & Q_e=0.4) in p.u. For a given 10% step change in input ΔP_m, the responses obtained for nominal, heavy and light load systems are depicted in terms of speed deviations. Fig 6, 7 and 8 show speed deviations, and Fig 9, 10 and 11 show rotor angle deviations of the systems considered (in the order mentioned above). Table 1 shows the time domain indices of speed deviation responses for different loading conditions in terms of peak value and settling time and also the values of objective function minimization. Table 2 shows the time domain indices of rotor angle deviation responses. Table 3 shows the parametric values of damping controllers obtained using ETLOBA. Fig 12, 13 and 14 show the convergence characteristics of ETLOBA towards optimum values for nominal, heavy and light loaded systems respectively. Figures, tables 1and 2 clearly portray the supremacy of ETLOBA in designing the UPFC based damping controllers for dynamic stability enhancement of SMIB power system considered for the study.

VII. CONCLUSIONS

In this paper a new intelligent method of designing the coordinated UPFC controller based PSS, tuned with ETLOBA algorithm using Philip-Heffron's model for SMIB was proposed. Various simulations for different loading conditions have been explored, which indicates the superior performance of the proposed system when tuned properly.

Table 1. Time domain indices for speed deviation responses and objective function minimization values

	Nominal System			Light System			Heavy System		
	1st Peak over shoot	Settling time (sec)	Obj fun. Mean (std)	1st Peak overshoot	Settling time (sec)	Obj fun. Mean (std)	1st Peak over shoot	Settling time (sec)	Obj fun. Mean (std)
PSO – PSS [1]	2.07e-03	NaN		3.40e-03	NaN		3.81e-03	9.96	
PSO – m_B [1]	1.54e-03	7.72		2.48e-03	9.76		2.02e-03	6.74	
PSO - δ_E [1]	1.72e-03	9.58		2.76e-03	7.73		5.11e-03	9.35	
ETLOBA – m_B	1.21e-03	4.32	4.68e-04 (6.91e-07)	2.09e-03	5.01	7.73e-04 (2.86e-05)	1.76e-03	5.29	2.691e-03 (4.38e-05)
ETLOBA - δ_E **,** δ_B**(light system)**	1.66e-03	4.45	7.97e-04 (2.72e-06)	2.68e-03	7.04	6.04e-03 (3.23e-03)	4.47e-03	6.58	9.471e-03 (6.49e-03)
ETLOBA Coor m_B **-**δ_E	**1.10e-03**	**4.26**	3.79e-04 (2.56e-07)	**1.65e-03**	**3.46**	6.06e-04 (2.73e-05)	**1.60e-03**	**5.25**	1.111e-03 (8.69e-06)

Table 2. Time domain indices for rotor angle deviation responses

	Nominal System		Light System		Heavy System	
	1st Peak over shoot	Settling time (s)	1st Peak over shoot	Settling time (s)	1st Peak over shoot	Settling time (s)
PSO – PSS [1]	0.24	NaN	0.362	NaN	0.674	9.63
PSO – m_B [1]	0.26	7.38	0.335	9.24	0.627	8.76
PSO - δ_E [1]	0.246	9.53	0.458	7.58	1.249	9.54
ETLOBA – m_B	0.115	**4.76**	0.416	7.42	0.462	8.38
ETLOBA δ_E **and**δ_B**(light system)**	0.278	5.88	0.168	**6.59**	0.89	8.24
ETLOBA Coor m_B **-**δ_E	**0.106**	5.23	**0.166**	8.62	**0.367**	**7.82**

Table 3Parametric values of the UPFC damping controllers obtained using ETLOBA

Parae meters	Nominal Loading				Light Loading				Heavy Loading			
	Individual tuned Controllers		Coordinated tuned Controllers		Individual tuned Controller		Coordinated tuned Controllers		Individual tuned Controller		Coordinated tuned Controller	
	m_B	δ_E	m_B	δ_E	m_B	δ_B	m_B	δ_B	m_B	δ_E	m_B	δ_E
K_p	100.0	- 67.13	66.22	-30.79	94.66	-87.81	72.36	-100.0	100.0	-100.0	50.50	-92.82
T_1	0.729	4.908	2.439	0.100	1.378	3.172	0.698	5.000	1.345	0.100	3.763	0.100
T_2	0.100	1.327	4.189	2.680	0.100	3.465	0.100	1.166	0.100	0.518	2.438	0.881
T_3	5.000	1.929	1.990	0.100	5.000	4.934	4.297	5.000	2.546	0.100	1.137	0.100
T_4	3.001	0.941	0.100	0.643	2.959	0.100	0.967	1.405	2.456	0.493	0.100	1.822

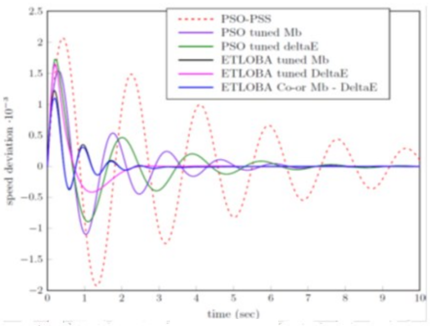

Fig 6

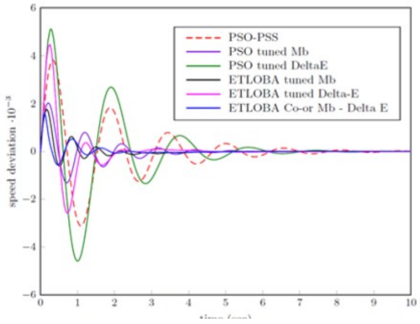

Fig 7

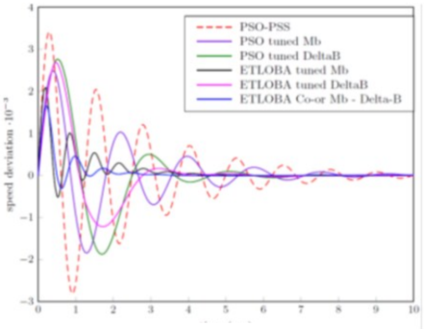

Fig 8

Fig 6, 7, 8 : speed deviations of nominal, heavy and light loaded systems respectively

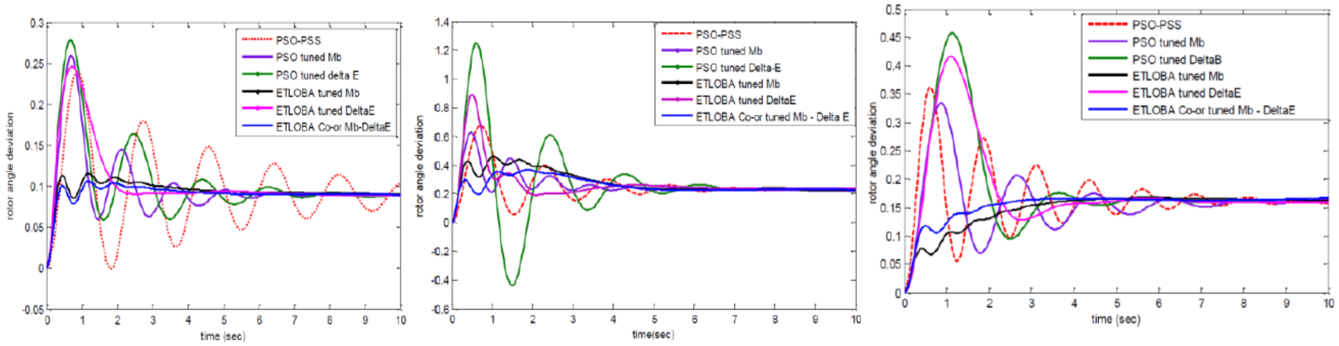

Fig 9 **Fig 10** **Fig 11**

Fig 9, 10, 11: Rotor angle deviations of nominal, heavy and light loaded systems respectively

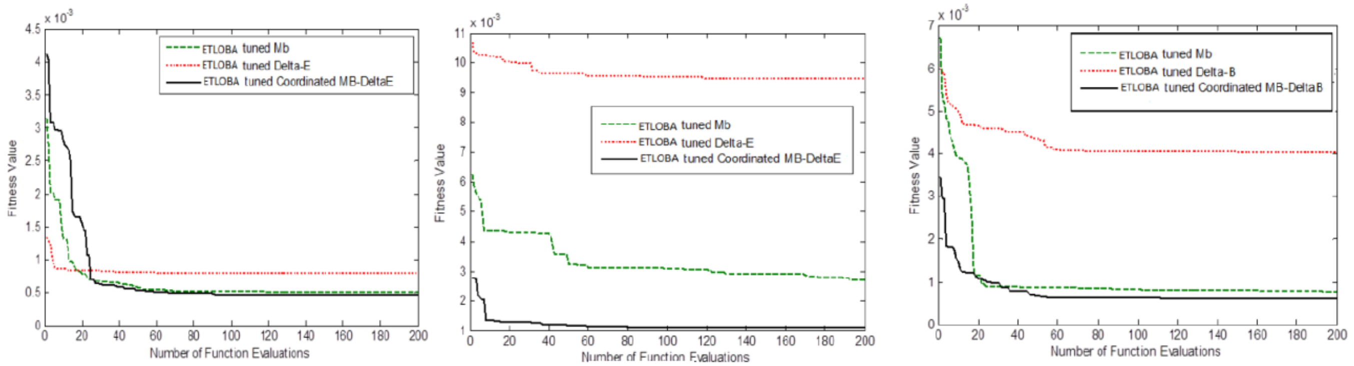

Fig 12 **Fig 13** **Fig 14**

Fig 12, 13 and 14: Objective function minimization plots of nominal, heavy and light loaded systems

REFERENCES

[1] A 12 AlAwami, Ali Taleb. " Design of Robust PSS and facts-based controllers for stability enhancement of power systems - .by Ali Taleb Al-Awami" /. 2004.

[2] Larsen, E.V.; Swann, D.A.; , "Applying Power System Stabilizers Part II: Performance Objectives and Tuning Concepts," *Power Apparatus and Systems, IEEE Transactions on* , vol.PAS-100, no.6, pp.3025-3033, June 1981.

[3] H F Wang. "A Unified Model for the Analysis of FACTS Devices in DampingPower System Oscillations — Part III : Unified Power Flow Controller." *IEEE Transactions* on Power Delivery, vol 15, no 3, July 2000, p 978.

[4] Guo, J.; Crow, M.L.; , "An improved UPFC control for oscillation damping". *IEEE Trans*. Power Syst., 25(1): 288–296, 2009.

[5] Abido, M.A.;.Abdel-Magid, Y.L.; ,"Analysis of power system stability enhancement via excitation and FACTS-based stabilizers",*Electric Power Elements & Systems*, Vol.32, No. 1, January2004,pp.75-91.

[6] D.P Kothari and I.J.Nagarath, "Modern Power System analysis", 4thed. TMH, New Delhi, 2011.

[7] Tambey, N.; Kothari, M.L.; , "Damping of power system oscillations with unified power flow controller (UPFC)," *Generation, Transmission and Distribution, IEE Proceedings-* , vol.150, no.2, pp. 129- 140, March 2003.

[8] R.V. Rao, V.J. Savsani and D.P. Vakharia, "Teaching-Learning-Based Optimization: A novel optimization method for continuous non-linear large scale problems", Information Sciences, 183 (1).

[9] M. Shokri, H.R. Tizhoosh, M.Kamel, "Opposition-based Q(λ) algorithm" *In Proc. IEEE World Congress on Comput, Intell,* Vancouver, BC, Canada, 2006, pp. 646-653.

[10] D.P. Kothari and J.S. Dhillon, "Power System Optimization", 2nd Ed., PHI, New Delhi, 2011