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Efficacy of GWO Optimized PI and Lead-lag Controller for Design of UPFC based Supplementary Damping Controller

Narayan Nahak[1], Ranjan Kumar Mallick[2]
[1]Departement of Electrical Engineering, Siksha 'O' Anusandhan University, Odisha, India
[2]Departement of Electrical and Electronics Engineering, Siksha 'O' Anusandhan University, Odisha, India

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ABSTRACT

On line tuning of FACTS based damping controller is a vital decisive task in power system. In this regard two things need to be addressed, one is selection of a proper controller and another one is selection of a powerful optimization technique. In this work Grey Wolf Optimizer (GWO) technique is proposed to tune parameters of PI and lead lag controller based on UPFC to damp intra plant and inter area electromechanical oscillations with single and multi machine power system. A broad comparison has been performed with eigen value analysis between optimized PI and lead lag damping controller subject to different disturbances in power system. The recently revealed GWO, standard PSO and DE techniques are explicitly employed to tune UPFC based PI and lead-lag controller parameters. The system response predicts that performance of GWO is much better than PSO and DE techniques, and also lead lag controller is a better choice than PI controller pertaining to design of UPFC based damping controller.

Corresponding Author:

Ranjan Kumar Mallick,
Departement of Electrical and Electronics Engineering,
Siksha 'O' Anusandhan University,
Bhubaneswar, Odisha, India.
Email: rkm.iter@gmail.com

1. INTRODUCTION

Modern power system network are interconnected with each other for better control, operation and security purpose. So the stability of power system has been a challenging issue of research. This work focuses on power system dynamic stability pertaining to damping of power system oscillations. The inter connection of different networks instigating low frequency oscillations has become an all time issue for power system. These oscillations may integrate and finally lead to loss of synchronism [1]. Power system stabilizer (PSS) has been traditionally used to damp these oscillations. But, the demerit of PSS lies on large change in voltage profile, not capable to meet sudden disturbances and operation in lead power factor [2]. On the other hand FACTS based PSS are becoming more popular due to several reasons like easy online tuning, flexibility in operation [3, 4]. The FACTS based controller may employ UPFC, TCSC, SSSC etc., but UPFC is more versatile with three degrees of freedom and can provide unconstrained series voltage [5, 6]. Steady state model of power system with UPFC has already been reported earlier [7].

The small signal Heffron Phillips model presented in [8] has been used for dynamic stability assessment. But, a systematic approach to design the controller has not been reported here [9]. Different robust techniques have been compared in [10] to design the damping controller. For supplementary controller based on UPFC to damp oscillations, it may be of PI type or lead-lag type. Now the matter of selection of PI or lead-lag controller is a decisive approach. In this work a broad comparison has been performed between optimized PI and lead-lag structure for selection of damping controller. The next part of this work is online tuning of PI and lead-lag controller, for which a suitable optimization technique is to be adopted. PSO technique has been very popular due to so many advantages and has been used to design damping controller [11, 12]. PSO is a simple and robust method, but it may trap in local optima when handling a complex problem.

Differential Evolution (DE) is an evolutionary type algorithm being used to design SSSC based damping controller in [13]. Recently other techniques like adaptive PSO, GA, GSA etc. have been reported for optimal controller design [14-16]. For optimal controller design metaheuristic techniques are gaining more popularity now a days. These techniques are simple, efficient and can handle any complex optimization problem [17]. GWO is a recently revealed optimization technique [17] inspired by the behavior of Grey Wolfs to hunt for a prey. GWO has so many advantages as compared to prevailing optimization techniques like its simplicity, robustness, straight forwardness and can easily handle any complex optimization problem without trapping in local optima [18]. Hence GWO has been used here to tune UPFC based PI and lead-lag controller for damping of oscillations in power system, and it has been compared with standard PSO and DE techniques to justify its supremacy.

The main contribution of this work includes: (i) the supplementary UPFC based controller is designed with PI and lead-lag controller. (ii) The parameters of controllers are optimized by PSO, DE and recently developed GWO techniques. (iii) A broad comparison has been performed between optimized PI and lead-lag controller. (iv) This work has been extended to multi machine system with a different kind of negative reactive power loading for complete validation. (v) Detail eigen value analysis has been performed for each operating condition to justify the efficacy of most deemed fit GWO optimized lead-lag controller

2. THE SINGLE MACHINE POWER SYSTEM UNDER STUDY

In this case a single machine connected to infinite bus is considered as shown in Figure.1. The initial condition of the system is given in appendix A1. The UPFC consists of two voltage source converters (VSC) is connected between generator and infinite bus.One VSC is series connected and another is shunt connected with the line. UPFC has four control actions which are mB, δB, mE and δE. Out of which mB and δB are modulation index and phase angle of series VSC respectively. So on mE and δE are are modulation index and phase angle of shunt VSC respectively.

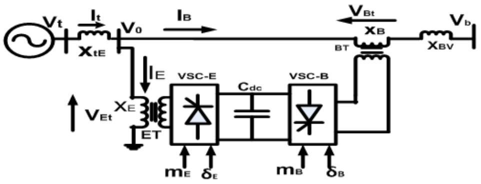

Figure 1. The SMIB system under study

2.1. DYNAMIC MODEL OF THE SYSTEM

2.1.1 Non Linear Model

By ignoring resistance of the line, non linear model of single machine power system can be represented by following equations [8]

$$\dot{\omega} = (\frac{P_i - P_e - D\Delta\omega}{M}) \tag{1}$$

$$\dot{\delta} = \omega_0 (\omega - 1) \tag{2}$$

$$\dot{E_q} = (-E_q + E_{fd}) / T_{d0} \tag{3}$$

$$\dot{E_{fd}} = \left[-E_{fd} + K_a (V_{ref} - V_t) \right] / T_a \tag{4}$$

$$V_{dc} = \frac{3m_E}{4C_{dc}} \left(I_{Ed} \sin\delta_E + I_{Eq} \cos\delta_E \right) + \frac{3m_B}{4C_{dc}} \left(I_{Ed} \sin\delta_E + I_{Eq} \cos\delta_E \right) \tag{5}$$

The real power balance between shunt VSC and series VSC can be represented by equation-(6) as

$$\mathrm{Re}(V_B I_B^* - V_E I_E^*) = 0 \tag{6}$$

2.1.2. Linear Dynamic Model

The linear model of power system can be obtained by linearizing the non linear model around the initial operating condition represented by following equations.

$$\dot{\Delta\delta} = \omega_0 \Delta\omega \; (7) \quad \dot{\Delta\omega} = \left(\frac{-\Delta P_e - D\Delta\omega}{M} \right) \tag{7}$$

$$\Delta\dot{E}_q = (-\Delta E_q + \Delta E_{fd}) / T_{d0} \tag{8}$$

$$\Delta\dot{E}_{fd} = \left[-\Delta E_{fd} + K_a (\Delta V_{ref} - \Delta V_t) \right] / T_a \tag{9}$$

$$\begin{aligned} \Delta V_{dc} &= K_7 \Delta\delta + K_8 \Delta E_q' - K_9 \Delta V_{dc} + K_{cE} \Delta m_E \\ &+ K_{c\delta e} \Delta\delta_E + K_{cb} \Delta m_B + K_{c\delta b} \Delta\delta_B \end{aligned} \tag{10}$$

Where

$$\Delta P_e = K_1 \Delta\delta + K_3 \Delta E_q' + K_{pd} \Delta V_{dc} + K_{pe} \Delta m_E + K_{p\delta E} \Delta\delta_E + K_{pi} \Delta m_B + K_{p\delta b} \Delta\delta_B \tag{11}$$

$$\Delta E_d = k_4 \Delta\delta + k_3 \Delta E_q' + k_{qd} \Delta V_{dc} + k_{qe} \Delta m_E + k_{q\delta_E} \Delta\delta_E + k_{qb} \Delta m_B + k_{q\delta_B} \Delta\delta_B \tag{12}$$

$$\Delta V_t = k_5 \Delta\delta + k_6 \Delta E_q' + kV_d \Delta V_{dc} + k_v \Delta m_E + k_{v\delta E} \Delta\delta_E + k_{vb} \Delta m_B + k_{v\delta b} \Delta\delta_B \tag{13}$$

3. SMALL SIGNAL MODEL OF SINGLE MACHINE SYSTEM

The Heffron Philips transfer function model of single machine power system is shown in Figure 2. The ‘K’ constants of this model are calculated with reference to initial operating condition and system parameters [9]. The initial operating condition is given in appendix A1. This model has been developed by using Equation (7-11) and modification of basic Heffron Philips model with UPFC.In this model [ΔU] is the control vector in column form and [K_{pu}], [K_{vu}], [K_{qu}], [Kcu] vectors are in row form given by following expressions.

[ΔU]=$[\Delta m_E \Delta\delta_E \Delta m_B \Delta\delta_B]^T$,[$K_{pu}$]=$[K_{pu}\ K_{p\delta e} K_{pb}\ K_{p\delta b}]$,[$K_{vu}$]=$[K_{ve} K_{v\delta e} K_{vb}\ K_{v\delta b}]$, [$K_{qu}$]=$[K_{qe} K_{q\delta e} K_{qb}\ K_{q\delta b}]$, [$K_{cu}$] =$[K_{Ce} K_{C\delta e} K_{Cb} K_{C\delta b}]$

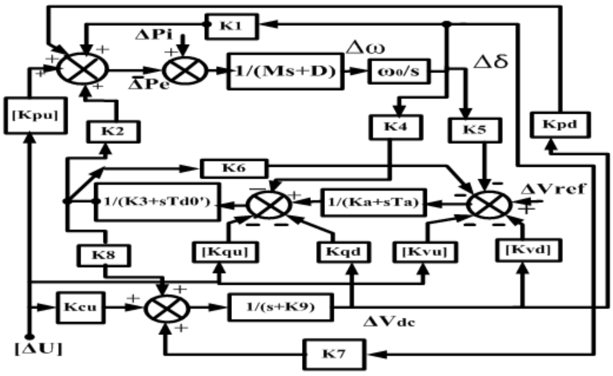

Figure 2. Modified Heffron-Phillips model with UPFC

4. DAMPING CONTROLLER

The objective of damping controller is to provide supplementary control action to the generator to damp low frequency oscillations and this action is based on UPFC. The UPFC has four control actions m_B, δ_B, m_E and δ_E. Out of these four actions two control actions are taken here to provide damping torque because, as per researches these are best control actions to design damping controller [6]

4.1 Proportional Integral (PI) structure

The structure of a popular PI controller is given in Figure 3. The input to PI controller is speed deviation, being the error signal and output of controller provides the control action to be executed. K1 and K2 are the gains of proportional and integral controllers respectively, which are to be optimized by the optimization techniques.

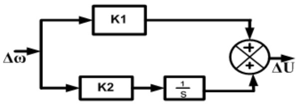

Figure 3. PI controller structure

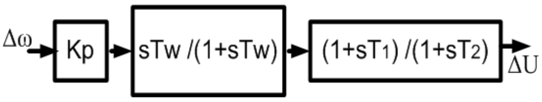

Figure 4. Structure of lead-lag controller

4.2 The lead-lag structure

The lead-lag controller has three blocks, gain, wash out and phase compensation as shown in Figure 4. The gain required by the controller is provided by the gain block of gain Kp. The washout block acts like a high pass filter with time constant (Tw) 1-20 sec. Choosing of this value is not so crucial and is taken as 10 sec. in this work. The phase compensation block provides necessary phase lead there by compensating for the required phase lag between input and output of controller with time constants T1 and T2. Now Kp, T1 and T2 are to be optimized by the optimization techniques.

5. OBJECTIVE FUNCTION

The problem of damping of oscillation is put to an objective function, which is of ITAE type. For the objective function, the disturbance considered is 10 percent rise in mechanical input power to generator. The objective function is represented by Eq-29, which considers speed, line power and dc bus voltage deviation.

$$J = \int_0^{tsim} t|\Delta\omega|dt + \int_0^{tsim} t|\Delta V_{dc}|dt + \int_0^{tsim} t|\Delta P_e|dt \tag{14}$$

The problem now is minimization of ‘J’ subject to following constraints

$$\begin{aligned} &K1_i^{min} \le K1 \le K1_i^{max} \\ &K2_i^{min} \le K2 \le K2_i^{max} \\ &K_{pi}^{min} \le K_{pi} \le {}^{Kpimax} \\ &T_{1i}^{min} \le T_{1i} \le T_{1i}^{max} \\ &T_{2i}^{min} \le T_{2i} \le T_{2i}^{max} \end{aligned} \tag{15}$$

Where t_{sim} is the simulation time, the superscripts min and max are the lower and upper limiting values of respective parameters. K1, K2 are only for PI controller and Kp, T1, T2 are for lead-lag controller. The range of K1 and Kp has been taken from 1 to 100. The range of K2, T_1 and T_2 is taken from 0 to 1. Now the problem is to optimize these parameters by Grey Wolf Optimiser

6. PSO TECHNIQUE

PSO is a simple and fast population based metaheuristic technique [11]. In PSO the particles are allowed to move around the search space in multi dimensional path. The position of a particle is updated by its own experience and neighbor particle. Efficacy of PSO is even challenging to genetic algorithm. The velocity of swarm is given by Equation 31 as given below. The velocity of each swarm can be given by:

$$v_i^{k+1} = wv_i^k + c_1 ran_1(P_{i,pbest}^k - x_i^k) + c_2 ran_2(P_{i,gbest}^k - x_i^k) \quad (16)$$

Where, c_1 and c_2 are the acceleration coefficients, *w* is the inertial weight varying between 0.9 to 0.4 ran_1 and ran_2 are the two random variables in the range of [0,1]. The swarm position is updated by

$$x_i^{new} = x_i + v_i \quad (17)$$

The best solution for the next iterations is given by

$$x_i^{k+1} = \begin{cases} \dfrac{x_{i,new} \text{ if } f(x_{i,new}) \le f(x_i)}{x_i \text{ otherwise}} \end{cases} \quad (18)$$

7. DE TECHNIQUE

It is an evolutionary algorithm type technique, where the process of searching is guided by distance as well as direction from current population [13].The most important search mechanism in DE is mutation. In DE, a trail vector is obtained by operating the target and difference vector. In a M-dimensional search space mutant vector can be obtained as

$$v_{i,\, g+1} = x_{a1,\, g} + F * (x_{a2,\, g} - x_{a3,\, g}) \quad (19)$$

Where a_1, a_2 …..are random integers.

To expand the diversity of the parameters crossover is done where parent vector is mixed with mutated vector to produce a trail vector $v_{ji,g+1}$ as given by

$$\begin{matrix} v_{ji,g+1} & \text{if } (randmj \le CRO) \text{ or, } j = j_{randm} \\ x_{ji,g+1} & \text{if } (randmj > CRO) \text{ or, } j \ne j_{randm} \end{matrix} \quad (20)$$

j=1,2,3………..M, CRO is the crossover constant [0,1].

8. GREY WOLF OPTIMIZER (GWO) TECHNIQUE

It is a swarm intelligence type metaheuristic algorithm recently published [17]. This technique has been imitated by the way Grey Wolfs hunt for their prey. They remain within a pack or group. The wolfs are ranked in the group as alpha (α), beta (β), delta (δ) and omega (ω). The most deemed fit solution is provided by the position of α followed by β, δ and rest solution by position of ω. When the hunting process begins, they encircle the prey, which is mathematically formulated as:

$$\vec{D} = \left| \vec{C}.\vec{X}_P(t) - \vec{X}(t) \right| \quad (21)$$

$$\vec{X}(t+1) = \left| \vec{X}_P(t) - \vec{A}.\vec{D} \right| \quad (22)$$

Where, the current iteration is represented by‘t’. $\vec{A},\vec{C}$ being coefficient vectors and $\overrightarrow{X_P}$ is the position vector of prey. The grey wolf position is denoted by $\vec{X}$.

A and C vectors are given by

$$\vec{A} = 2.\vec{a}.\vec{r}_1 - \vec{a} \quad (23)$$

$$\vec{C} = 2.\vec{r}_2 \quad (24)$$

Where, r_1 and r_2 are random vectors between [0 1]. In the course of iterations, the component ‘a’ decreases from 2 to 0 linearly for each iteration.

For initializing the hunting process, it is assumed that α , β and δ wolves know the exact position of prey and the current position of these wolves are updated by the following equations.

$$\vec{D}_\alpha = \left|\vec{C}_1.\vec{X}_\alpha - \vec{X}\right|, \vec{D}_\beta = \left|\vec{C}_2.\vec{X}_\beta - \vec{X}\right|, \vec{D}_\delta = \left|\vec{C}_3.\vec{X}_\delta - \vec{X}\right| \tag{25}$$

$$\vec{X}_1 = \vec{X}_\alpha - \vec{A}_1.(\vec{D}_\alpha), \vec{X}_2 = \vec{X}_\beta - \vec{A}_2.(\vec{D}_\beta), \vec{X}_3 = \vec{X}_\delta - \vec{A}_3.(\vec{D}_\delta) \tag{26}$$

To find the best location of prey, an average value of current position of α, β and δ wolves is taken as:

$$\vec{X}(t+1) = \frac{\vec{X}_1 + \vec{X}_2 + \vec{X}_3}{3} \tag{27}$$

The flow chart of GWO technique is given in Figure 5.

9. SIMULATION &RESULTS

The prime objective in this work is to choose a suitable structure, out of PI and lead-lag for design of damping controller and optimizing the controller for enhancing the efficacy of controller. At first single machine system is considered and than the work is extended to multi machine system for complete validation. Here objective function in Eq-14 is taken for minimization and for multi machine system, only speed deviation is considered for minimization.

9.1. Single machine system

The data for single machine system is given in appendix A1, where the initial loading considered for simulation is taken as Pe=0.8, Qe=0.17. The system is provided with UPFC based supplementary controller to damp system oscillations subject to disturbances in power system .The simulation has been carried with MATLAB 7.10.0 version. The optimized parameters are obtained after 30 numbers of independent runs and given in Table-1. As per literature [6], the most suitable control actions to design damping controller are based on modulation index of series converter (VSC), which is m_B and phase angle of shunt VSC, which is δ_E. So these two control actions are taken here.

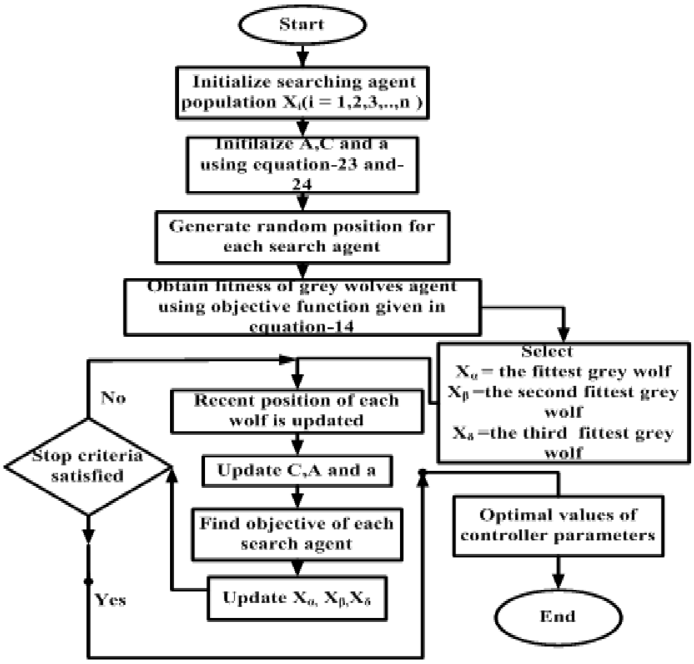

Figure 5. Flow chart of GWO algorithm

Table-1.Optimized Parameters

Controller	PI controller				Lead-lag controller					
Control action ⇨	m_B based		δ_E based		m_B based			δ_E based		
Algorithm ⇩	K1	K2	K1	K2	Kp	T1	T2	Kp	T1	T2
PSO	97.1605	0.4673	28.1074	0.2991	65.168	0.821	0.682	22.608	0.79	0.606
DE	84.131	0.1531	50. 535	0.2217	55.59	0.806	0.474	28.96	0.655	0.964
GWO	71.1907	0.4054	66.0896	0.8611	59.98	0.854	0.801	39.98	0.1403	0.136

9.2. Different loading conditions

9.2.1 Nominal loading case

In this condition Pe=0.8, Qe=0.17 and the reactance of line is,Xe=0.5. With this loading the input prime mover power to generator has been increased by 10 percent and optimized PI and lead-lag controllers are employed to tackle the disturbance. The Figure 6 shows speed deviation with optimized PI and lead-lag controllers with m_B control action. In the legends of figure, PI and lead-lag represents optimized PI and lead-lag controllersrespectively.The system eigen values are given in Table-3. From responses it was observed that GWO optimized lead-lag controller providing much better result as compared to others.

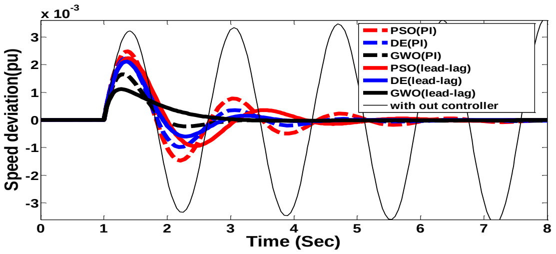

Figure 6. Speed deviation for nominal loading

9.2.2 Light loading case

In this condition Pe=0.65, Qe=0.2324 and the reactance of line is Xe=0.5. With light loading condition, the system responses are obtained m_B and $\delta_E$control actions employing optimized PI and lead-lag controller. Figure 7 and 8 represent the speed deviation response with m_B and $\delta_E$control actions respectively by PSO, DE and GWO optimized PI and lead-lag controllers. The system eigen values are given in Table 3. From system response it is clear that GWO optimized lead-lag controller damps system oscillations to a large extent as compared to PI optimized controller.

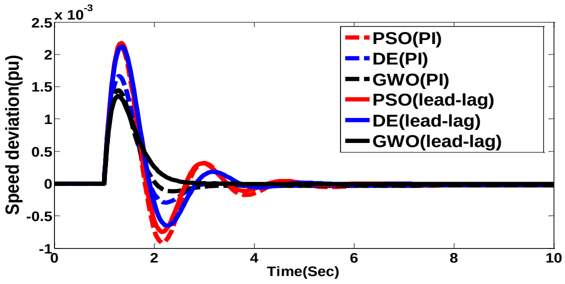

Figure 7. Speed deviation for light loading (m_B)

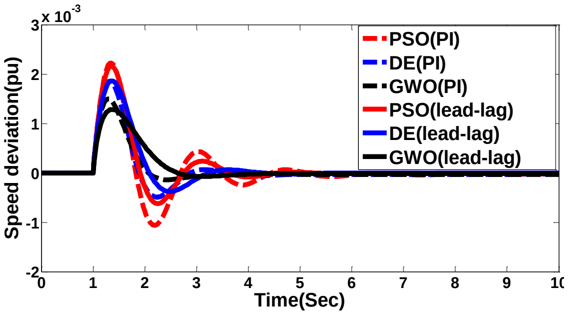

Figure 8. Speed deviation for light loading (δ_E)

9.2.3 Heavy loading case

In this condition Pe=1.11, Qe=0.03 and the reactance of line is Xe=0.5. With this loading the system is provided with supplementary controller to damp system oscillations. The system responses are obtained with m_B and $\delta_E$control actions employing optimized PI and lead-lag controller. Figure 9 and 10 represent the speed deviation response with m_B and $\delta_E$control actions respectively by PSO, DE and GWO optimized PI and lead-lag controllers.The system eigen values are given in Table-3. Here also after comparison it was found that GWO optimized lead-lag controller providing much better result as compared to other optimized controllers

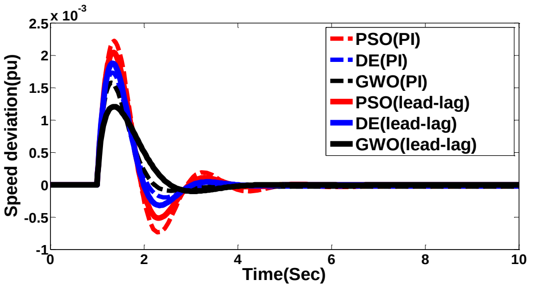

Figure 9. Speed deviation for heavy loading (m_B)

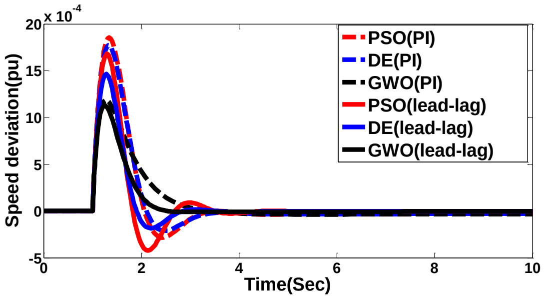

Figure 10. Speed deviation for heavy loading (δ_E)

10. MULTI MACHINE SYSTEM

In this work a three machine power system as shown in Figure 11 is taken into consideration [8].For three machines IEEE-ST1A excitation system is taken. The parameters for machine-1 are taken same as single machine system considered earlier as in appendix A1 and for machine 2 and 3 are given in appendix A2. The UPFC is connected at the midpoint of transmission line between bus-3 and 4.

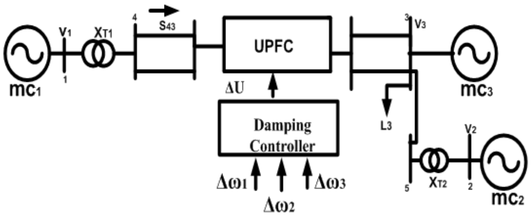

Figure 11. A three machine power system

With loading L_3 at bus-3, the input mechanical power to generator is raised by 10 percent.The loading for bus-3 is a rare load with negative value of reactive power as given in appendix A2.

The input to controller is the sum of speed deviation of the all three machines and the objective function in Eq-14 considers only the speed deviation as input signal. The optimized parameters for multi machine system are given in Table-2 with optimized PI and lead-lag controller. The inter area speed deviations ω_{12} with m_B and δ_E control action are shown in Figure 12 and 13 respectively. So on inter area speed deviations ω_{13} with m_B and δ_E control action are shown in Figure 14 and 15 respectively. From inter area speed deviation response it has been observed that GWO optimized lead-lag controller damps oscillation much better as compared to others.

Table-2.Optimized Parameter with PI Controller

Control action	m_B based		δ_E based		m_B based			δ_E based		
Algorithm	K1	K2	K1	K2	Kp	T1	T2	Kp	T1	T2
PSO	33.2137	0.6153	35.1959	0.3042	58.6455	0.6969	0.6614	48.0247	0.3475	0. 5832
DE	43.8687	0.428	40.8029	0.7763	55.3714	0.4804	0.2158	64.6815	0.4241	0.6971
GWO	76.439	0.6225	48.4001	0. 593	58.7198	1	0.4884	64.7889	0. 5338	0. 5623

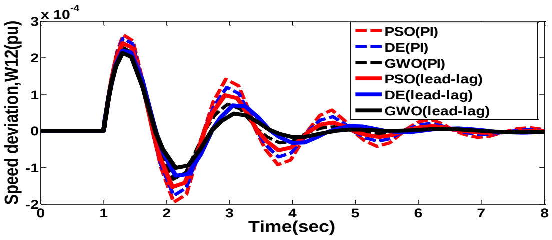

Figure 12. Speed deviation w_{12} with m_B based controller

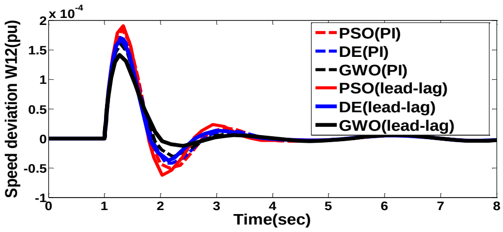

Figure 13. Speed deviation w_{12} with δ_E based controller

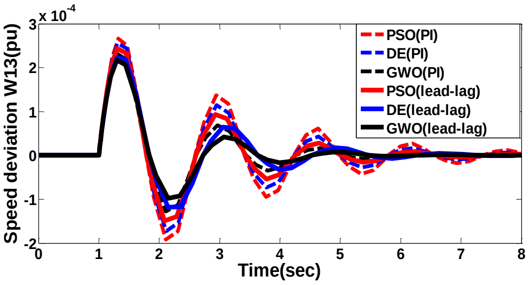

Figure 14. Speed deviation w_{13} with m_B based controller

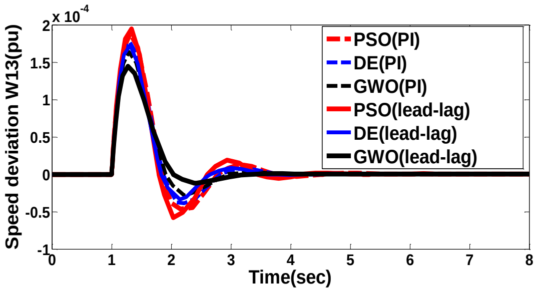

Figure 15. Speed deviation w_{13} with δ_E based controller

Table 3. System Eigen Values with Optimized PI and Lead-Lag Controller

	Lead-lag controller			PI controller		
	0.65	0.8	1.11	0.65	0.8	1.11
Pso	-93.72,-7.34	-92.5487,-8.6299,-1.3360 ± 3.7332i,-1.0524,	-88.398,-12.7264	-92.5926, -8.2122	-92.5935 ,-8.1739	-92.5958 , -8.0934
delE	-1.23 ± 3.584i	-0.1090,-0.0030	-1.716 ± 3.7149i	-0.9414 + 3.7393i	-1.1278 + 3.5454i	-1.8711 + 2.8753i
	-1.3811,-0.0032		-2.2042,-0.1046	-0.9414 - 3.7393i	-1.1278 - 3.5454i	-1.8711 - 2.8753i
	-0.1085		-0.0025	-0.0426	-0.0399	-0.0305
	-0.0027,-93.6793	-0.0041,-92.5431	-0.0035,-88.383	-92.588, -8.321	-92.58,-8.3408	-92.5953, -8.1126
de	8.4565,-1.4540 ± 2.778i,-0.1074	-8.8488,-1.2384± 1.3364i,-0.1050	-12.9228	-1.5769 + 3.4352i	-2.0744 + 2.9699i	-2.0447 + 2.7431i
	-0.0032	-0.003	-2.312 ± 2.4345i	-1.5769 - 3.4352i	-2.0744 - 2.9699i	-2.0447 - 2.7431i
			-0.1068,-0.0025	-0.0445	-0.0413	-0.0304
	-93.5325,-16.685	-99.3084,-8.0211	-88.3464,-3.6316	-92.581,-8.5698	-92.5841, -8.5403	-92.5898, -8.7350
gwo	-7.1171,-1.7979 ± 1.7877i	-4.2478,-2.7124	-6.4108,-3.62	-2.4246 + 2.7495i	-2.6895 + 2.3118i	-5.5835, -1.8407
	-0.1143,-0.0032	-1.3156,-0.1042	-1.8020,-0.1114	-2.4246 - 2.7495i	-2.6895 - 2.3118i	-0.0324
		-0.0026	-0.0025	-0.0456	-0.0413	
Pso	-99.3200,-1.1816 ±3.8501i,-1.1826,-1.0659	-99.3111,-4.1973	-99.3112	-92.6074 , -8.0743	-92.6045, -8.0430	-92.6059, -7.9453
mB	-0.0028,-0.1033	-0.8762 ± 2.8858i	-1.483 ± 3.2073i	-1.0904 + 3.7862i	-0.6795 + 3.7538i	-1.2292 + 3.3170i
		-1.2029,-0.0026	-1.6221,-1.2053	-1.0904 - 3.7862i	-0.6795 - 3.7538i	-1.2292 - 3.3170i
		-0.1009	-0.0026,-0.1022	-0.0425	-0.0389	-0.0296
de	-0.0075,-	-0.0050,-	-0.0051,-99.3112	-92.6140,	-92.6052, -	-92.6097,

Table 3. System Eigen Values with Optimized PI and Lead-Lag Controller

	Lead-lag controller			PI controller		
gwo	99.313	99.3112		-8.0425	8.0401	-7.9047
	-1.3240± 3.4248i	-1.8296 ± 3.0960i	-1.809 ± 3.1088i	-2.1017 + 3.3319i	-0.8011 + 3.7303i	-2.1510 + 2.8122i
	-1.2104,-0.0028	-1.2090,-0.0026	-1.2089,-0.0026	-2.1017 - 3.3319i	-0.8011 - 3.7303i	-2.1510 - 2.8122i
	-0.1021	-0.103	-0.1029	-0.0426	-0.0389	-0.0297
	-99.3119,-3.3479 ±2.1202i,-1.4928	-99.3126,-8.0566	-99.313,-14.2445	-92.619, -8.0116	-92.6042, -8.0439	-92.6115,-7.8752
	-1.2449,-0.0029	-1.3800 ± 0.8389i	-1.532 ± 1.8282i	-2.6882 + 2.28828i	-0.8392 + 2.7613i	-2.5720 + 2.4395i
	-0.1058	-1.208,-0.0026	-1.2118,-0.0026	-2.6883, -2.8828i	-0.8392 - 2.7613i	-2.5720 - 2.4395i
		-0.1064	-0.1048	-0.0429	-0.0389	-0.0297

11. CONCLUSION

In this work UPFC based supplementary controller is employed to damp intra plant and inter area oscillations in power system. A broad comparison has been performed employing UPFC based PI and lead-lag controller to damp oscillations in power system subject to wide range of loading condition with detail eigen value analysis. Recently revealed GWO technique, PSO and DE techniques are explicitly used to tune the parameters of PI and lead-lag controllers. It has been found that for damping controller design lead-lag controller is a better choice than PI controller and also GWO optimization technique is much better than PSO and DE technique. Hence GWO optimized supplementary UPFC based lead-lag controller is much superior to damp power system oscillations.

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APPENDIX

Appendix (All the datas are in per unit unless mentioned except constants) Single machine infinite bus test system data

C_{dc}=1, H=4MJ/MVA, Ka=100, Ta=0.01, T_{d0}=5.044sec, D=0, $\delta_0=47.13^0$, V_b=1, V_{dc}=2, V_t=1, $X_B=X_E$=0.1, X_{BV}=0.3, X_d=1, X_E=0.1, X_d'=0.3, X_q=0.6, Xe=0.5

Multimachine system data

H_2=20, H_3=11.8, $D_2=D_3$=0, T'_{d02}=7.5 sec, T'_{d03}=4.7 sec, T_{dc}=0.01, K_{dc}=5, X_{q2}=0.16, X_{q3}=0.33, X_{d2}=0.19, X_{d3}=0.41, X'_{d2}=0.076, T_{A2}=0.01, K_{A2}=100, K_{A3}=20, T_{A2}=0.01, Z_{13}=j0.6(double lines), Z_{23}=j0.1, L_3=0.8-j1.253, $V_3=1<0^0$, $V_2=1<5^0$

BIOGRAPHIES OF AUTHORS

N. Nahak received the **B.E.** degree in electrical engineering from Utkal University, Bhubaneswar, India, & M.Tech in 2009 from KIIT University Bhubaneswar India. He is currently working as Assistant professor in Electrical engineering department of Siksha O Anusandhan University Bhubaneswar, Odisha. India. His research interest includes Flexible AC Transmission System & robust controller designs.

Ranjan Kumar Mallick received his degree in electrical engineering from Institution of engineers (india) in 1996 and M.E degree in power system engineering from VSSUT, burla in 2001. He received his phd from BPUT, Odisha in 2013. He is currently working as Associate professor in the department of EEE, ITER, S‘O’A university, Odisha, India. His research interests are application of power electronics and optimization techniques in power system such as facts controller, agc controller, strategic bidding, econnomic load dispatch, design of hvdc converters and voltage and frequency stability of interconnected power system. He is having 17 years of experience in teaching and research and published around 25 papers in international journal and conference.