Multivariable Controller Design for Unified Power Flow Controller Using Evolutionary Optimization Algorithms

S.A. Al-MAWSAWI, A. HAIDER, and S.A. Al-QALLAF
University of Bahrain, College of Engineering, Department of Electrical and Electronics Engineering

aalmossawi@uob.edu.bh, aakbar@uob.edu.bh, saa-1985@hotmail.com

Abstract
This paper discusses the design of a multivariable control for unified power flow controller using evolutionary optimization algorithms. It utilizes two biologically inspired optimization algorithms; the particle swarm optimization algorithm and biogeography optimization algorithms, to obtain the optimal set for the controllers of the UPFC. The UPFC is to control the active power flow through the line, regulate the AC bus voltage, regulate the DC link voltage, and damp the low frequency oscillations in the network through a set of PI controllers and a two stage lead lag compensator respectively. The obtained controllers are then verified through time domain simulation for different variable control to assess the capability of this multivariable control scheme.

Keyword--- FACTS, Power System Dynamics, Power System Oscillations, PSO, BBO

1 Introduction

In the past few decades the flexible AC transmission system (FACTS) controllers have become an interesting field of research, due to the range of solutions that they offer for the transmission network problems. The introduction of the power electronics devices in the power system was initially intended to overcome the steady state limitation of the network and to increase the power transfer capability of the transmission lines through the control of system parameters. However, the functionality of the FACTS controllers was not limited to the steady state problems but it was extended to solve transient and dynamic problems of the power system, hence increasing the system stability. In [1], Abido has reviewed and compared the FACTS based damping controllers based on their performance and other technical aspects.

The unified power flow controller (UPFC), was introduced by Gyugyi in [2]. The UPFC is one of the typical FACTS devices that can provide simultaneous control of all or selectively basic parameter of the power system (transmission voltage, line impedance, and phase angle) [3]. The UPFC is able to fulfill the functions of a STATCOM, SSSC, and a phase shifter hence realizing multiple control schemes. Moreover the UPFC is reported to be able to damp system oscillations, where a UPFC stabilizer was designed in to mitigate the torsional oscillations in [4]. From this it can be seen that the UPFC is a multi-input multi-output (MIMO) system.

Several references in literature have tackled the problem of designing MIMO controller for the UPFC. In [5], [6]and [7], a study of the dynamic interaction between the UPFC control variables was presented along with a proposed method of decoupling through the design of a M IMO PI controller in order to maintain the closed loop stability of the system. Another approach has been presented in [8], where the μ- synthesis decentralized UPFC controller was designed, through decomposing the MIMO system into a multi-input single output (MISO) systems in order to reduce the interaction between the variables. Taher *et al,* in [9] has presented and compared between three decentralized control schemes, theμ synthesis, the QFT method, and H∞ loop shaping for the UPFC controller design.

Population based, cooperative and competitive stochastic search algorithms have been very popular in recent years in the field of computational intelligence[10]. These algorithms proved to be a useful tool in many studies for designing FACTS based power oscillation damping (POD) controller, that provide good response characteristics. Sidhartha *et al* ,in [11] designed a TCSC based power system stabilizer using genetic algorithm (GA). In [12], an output feedback UPFC POD controller, in which PSO was used to evaluate time based objective function in order to find the optimal parameters for the controller. Similarly, chaotic optimization algorithm (COA) was used in [13] to design an output feedback UPFC controller. A lead-lag based POD controller was designed in [14], where imperialist competitive algorithm (ICA) was used to evaluate an eigenvalue damping ratio objective function was evaluated.

Al-Awami *et al* [15], [16], presented another approach in designing UPFC MIMO control system through using PSO to tune multiple controllers of the UPFC, DC voltage regulator, Power flow controller, and damping controller simultaneously, with the emphasis of the design was on the damping controller. The UPFC multiple controllers were tuned at a single operating point for multiple disturbances. The results were then simulated at a nonlinear system for a single system disturbance at different operating conditions.

In this paper a biogeography based optimization (BBO) algorithm, a new population based algorithm, is considered to design a multivariable UPFC controller. The UPFC controller utilizes a multiple PI controllers and a lead lag compensator in order to control the active power flow controller, regulate the AC bus voltage, regulate the DC link voltage, and to damp the low frequency oscillations in the network respectively. The BBO is used to evaluate a time based objective function in order to obtain the optimal set of controller parameters. The results were compared with a PSO based multivariable controller, in order to investigate its capability in finding the optimal controller parameters.

2 System Modeling

The system considered in this paper is illustrated in Figure.1, which shows a single machine infinite bus (SMIB) system with double transmission line circuits equipped with a UPFC. The UPFC consists of two three phase GTO based voltage source converters (VSC) connected back to back through a co mmon DC link capacitor. The shunt converter or the excitation converter is coupled to the system through an excitation transformer (ET). The series converter or the boosting converter is coupled to the system through a boosting transformer (BT).

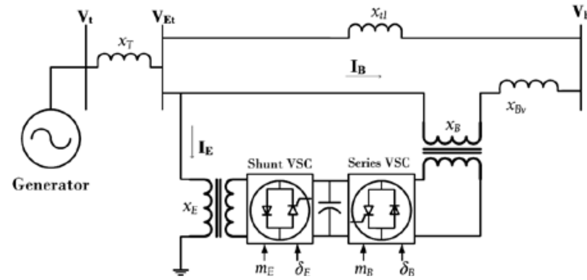

Figure 1: SMIB power system equipped with UPFC.

By applying Park's transformation, and by neglecting the resistances and transients of the excitation and boosting transformers the UPFC can be modeled as[17], [4], [18]:

$$\begin{vmatrix} v_{Etd} \\ v_{Etq} \end{vmatrix} = \begin{vmatrix} 0 & x_E \\ -x_E & 0 \end{vmatrix} \begin{vmatrix} i_{Etd} \\ i_{Etq} \end{vmatrix} + \frac{m_E v_{dc}}{2} \begin{vmatrix} \cos\delta_E \\ \sin\delta_E \end{vmatrix} \quad (1)$$

$$\begin{vmatrix} v_{Btd} \\ v_{Btq} \end{vmatrix} = \begin{vmatrix} 0 & x_B \\ -x_B & 0 \end{vmatrix} \begin{vmatrix} i_{Bd} \\ i_{Bq} \end{vmatrix} + \frac{m_B v_{dc}}{2} \begin{vmatrix} \cos\delta_B \\ \sin\delta_B \end{vmatrix} \quad (2)$$

$$\frac{dv_{dc}}{dt} = \frac{3m_E}{4C_{dc}} |\cos\delta_E \quad \sin\delta_E| + \frac{3m_B}{4C_{dc}} |\cos\delta_B \quad \sin\delta_B| \quad (3)$$

Where;

v_{Et} : Excitation transformer voltage

i_E : Excitation current

v_{Bt} : Boosting transformer voltage

i_B: Boosting current

C_{dc} : DC link capacitance

v_{dc} : DC link voltage

The UPFC has four control input signals where m_E and δ_E are the excitation branch amplitude and phase angles respectively, and m_B and δ_B are the boosting branch amplitude and phase angle respectively.

The nonlinear model of the generator shown in figure (1) is given as:

$$\frac{d\delta}{dt} = \omega_B(\omega - 1) \quad (4)$$

$$\frac{d\omega}{dt} = \frac{1}{M}(-D(\omega - 1) + P_m - P_e) \quad (5)$$

$$\frac{dE'_q}{dt} = \frac{1}{T'_{d0}}\left(-E'_q + E_{fd} - (x_d - x'_d)i_d\right) \quad (6)$$

$$\frac{dE_{fd}}{dt} = \frac{1}{T_A}\left(-E_{fd} + K_A\left(V_{ref} - V_t\right)\right) \quad (7)$$

Where;

$$P_e = v_d i_d + v_q i_q, v_q = E'_q - x'_d i_d, v_d = x_q i_q, V_t = \sqrt{\left(v_d^2 + v_q^2\right)},$$

$i_d = i_{TLd} + i_{Ed} + i_{Bd}$, and $i_q = i_{TLq} + i_{Eq} + i_{Bq}$

3 UPFC Multivariable Controller Design

The UPFC in this research is used in order to achieve the following functions:

1. Control active power flow through the compensated transmission line P_{e2} through using the boosting converter modulation index m_B as input control signal.
2. Regulate the AC bus voltage V_{Et} through using excitation converter modulation index m_E as input control signal.
3. Regulate the UPFC dc link voltage v_{dc} through using excitation converter phase angle δ_E as input control signal.
4. Damp the local mode oscillations of the system using excitation converter phase angle δ_E as the input control signal based on [17], [16], [15].

Hence the following figure illustrates the structure of the multiple controllers of the UPFC:

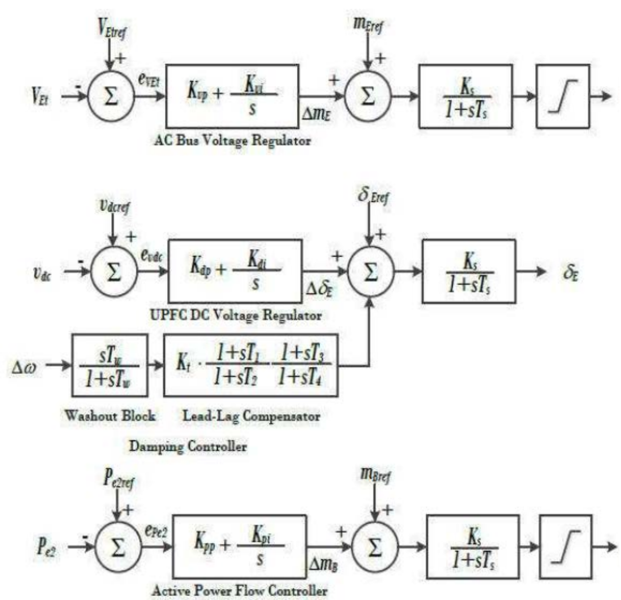

Figure 2: UPFC Multivariable Controller.

3.1 Evolutionary Optimization Algorithms

Biogeography Based Optimization:

Biogeography Based Optimization (BBO), introduced by Simon[19] is a population based evolutionary algorithm. Based on island biogeography theory, that is the nature way to achieve optimal condition of life through the distribution of species among islands.

If an optimization problem was to be solved using BBO, the independent variables of the problem are analogous to the suitability index variables (SIV) of an island, and the performance of the island is for the habitat suitability index (HSI). As in biogeography theory that high HSI islands having lower immigration rate thus it will be more reluctant to change than the low HSI islands having immigration rates. Therefore, a good individual will have low tendency to change than poor individuals, and vice versa for individuals with high HSI. Thus, the good individuals will share its features with the poor individuals. The addition of new features to poor individuals may raise the quality of those individuals. Immigration rates λ and emigration rates μ are functions of the number of species in the island. The migration model used in this paper is a l inear migration model where λ and μ are both linear functions of the cost.

BBO has two major operations:

1- Migration:

Algorithm (1) shows the pseudo code for the migration operator of BBO, for *N* population size and *n* number of SIV's per island:

Algorithm 1 Habitat Migration

for i = *1 to* N *for all individuals*
    $z_i = x_i$
    for s = *1 to* n
        Select x_i *with probability* $\propto \lambda_i$
        if rand(0,1) $< \lambda_i$ *then*
            for j = 1 to N
            Select x
                j with probability $\propto \mu_j$
                    if rand(0,1) $< \mu_j$ *then*
                        $z_i(s) \leftarrow x_j(s)$
                end if
            end for
        end if
    end for
end for

2- Mutation:

The second main operator in BBO is the mutation. Simon [19], has referred to mutation of SIV to be

analogous to the introduction of an excursion to a habitat that will drive it away from its equilibrium point and that can happen randomly.
Where; the probability count and the mutation rates can found in [19].
In algorithm (2) the pseudo code for the mutation operator of BBO is illustrated.

Algorithm 1 Habitat Mutation

```
for i = 1 to N
    Compute Probability P_i
    for s = 1 to n
        Select SIV x_i(s) with probability ∝ λ_i
        if rand(0,1) < m_i then
            Replace x_i(s) with a randomly generated
            SIV
        end if
    end for
end for
```

3.2 Particle Swarm Optimization

Particle swarm optimization (PSO) was introduced by Kennedy and Eberhart in 1995, [20]. This algorithm searches the space of an objective function by adjusting the trajectories of individual particles. The movement of a s warming particles consists of two major components: stochastic component and a deterministic component. Each particle is attracted toward the position of the current global best g_{bst} and its own personal best location p_{bst} in history, while in the same time it has tendency to move randomly [21]. PSO searches for an optimum by moving the particles through the search space. At each time step, t, and the position $x_i^{(t)}$ of the particle i is modified by adding the particle velocity to the previous position vector:

$$\vec{x}_i^{(t)} = \vec{x}_i^{(t-1)} + \vec{v}_i^{(t)} \tag{8}$$

The velocity vector determines the step size inside the search space and direction of the particle. The velocity vector is determined as:

$$\vec{v}_i^{(t)} = \omega \vec{x}_i^{(t)} + c_1 \vec{r}_1 \left(\vec{x}_{pbst,i} - \vec{x}_i^{(t)} \right) + c_2 \vec{r}_2 \left(\vec{x}_{gbst} - \vec{x}_i^{(t)} \right) \tag{9}$$

where ω is the inertia weight , controlling the influence of the previous velocity values on the new velocity. c_1 and c_2 are the acceleration coefficients used to scale cognitive and social components respectively. r_1 and r_2 are vectors with each component sampled from a uniform distribution $U(0, 1)$; x_{pbst},i is the i^{th} particle best location attained through generations and x_{gbst} is the global best location found in the swarm.

Based on [22], the basic PSO suffered from undesirable dynamical properties and to avoid those there was the need to limit the particle velocities in order to control their trajectories. Based on [23], to keep the velocity within sensible bounds by putting limits on the maximum that the particle velocity, and that has been adopted in this research paper.
In equation (9), the inertia weight was define to control the velocity of the particle from one generation to the next, as if it was not defined the velocity tends to become constant. However, it was found empirically that decreasing inertia weight during the optimization process may provide better performance.

3.3 Controller Design

In order to employ the optimization algorithms for the design of a M IMO control system an objective function is to be optimized. There were several approaches that have been introduced in literature, in [15], an ITAE based objective function was to be minimized, the objective function contained all the errors of all controlled variables in order to tune the controllers simultaneously. The system was given two disturbances: an impulse disturbance in the input mechanical power, and a step change in the setpoint of the power flow in the compensated line. The optimization was carried at a single operating point. In this paper a single operating point optimization will be carried out first with the same structure as in [15] in order to find the optimal set of gains for PI controllers and the gain and the time constants for a two stage lead-lag compensator to damp power system oscillations. The difference in here, is that an AC bus voltage regulator will be incorporated in the system and the disturbances introduced will be:

1. A 10% step change in mechanical power P_m
2. A 2.5% step change in setpoint of P_{e2}

In order to find the optimal set of gains and time constants the following objective function is considered:

$$J_t = \alpha \int t|\Delta\omega|\,dt + \beta \int t|\Delta P_{e2}|dt + \gamma \int t|\Delta v_{dc}|dt + \rho \int t|\Delta V_{Et}|dt \tag{10}$$

The above objective function is to be minimized:

$$\begin{gathered}\min J_t\\ Subject\ to\\ K_{pp}^{min} \le K_{pp} \le K_{pp}^{max}\\ K_{pi}^{min} \le K_{pi} \le K_{pi}^{max}\\ K_{dp}^{min} \le K_{dp} \le K_{dp}^{max}\\ K_{di}^{min} \le K_{di} \le K_{di}^{max}\\ K_{vp}^{min} \le K_{vp} \le K_{vp}^{max}\\ K_{vi}^{min} \le K_{vi} \le K_{vi}^{max}\\ K_{p}^{min} \le K_{p} \le K_{p}^{max}\\ T^{min} \le T \le T^{max}\end{gathered} \tag{11}$$

It can be seen that the objective function is a sum of the ITEA performance index of each control output. Furthermore, each part of this objective function is weighted to give emphasis on the desired output. The weights were found through fine tuning and given as: $\alpha = 100, \beta = 1, \gamma = 50, \rho = 1$.

The control system design is done through optimizing the objective function in (10) under nominal loading condition, where the population size considered is 150 and total generation of 100. The BBO maximum mutation is 0.05, and for PSO the acceleration coefficients are chosen as $c_1 = c_2 = 2.05$, and ω is to decrease from 0.9 to 0.4 as a function of the generation, based on [24]. With these conditions the following results were obtained:

Table 1: Optimal Control System Parameters and Cost Function Value.

Controller Parameter	*BBO Obtained Value*	*PSO Obtained Value*
K_p	-86.1999	-81.5887
T_1	0.6406	0.85137
T_2	0.6977	0.6319
T_3	0.0726	0.0133
T_4	0.4472	0.3575
K_{pp}	-0.2228	0.2730
K_{pi}	3.1689	1.4484
K_{dp}	-3.0814	-8.0792
K_{di}	-4.6577	-4.6412
K_{vp}	2.1841	2.2523
K_{vi}	0.7192	5.5808
J_t	2.7011	2.2871

From table 1, it can be seen through the comparison of the value of objective function attained that PSO has a superior performance over BBO for the following problem.

4 Simulation Results

For the purpose of comparison between the controllers performance there are a set of tests that are to be evaluated in order verify the superiority of a controller over the other, and these tests are:

4.1 Setpoint Variation

The UPFC is initial set to controller the power flow through the transmission line such that 50% of the generated power is carried by each of the lines. In this test the setpoint of the power flow controller is varied from its initial setting by -15% to 15% change in the setpoint. Both of the obtained multivariable controllers are tested under nominal loading condition of the generator.

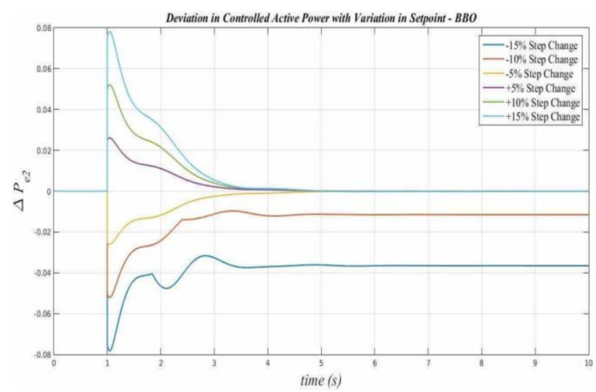

Figure 3: Deviation in line power flow ΔP_{e2} BBO tuned MIMO control system under variation of power flow setpoint.

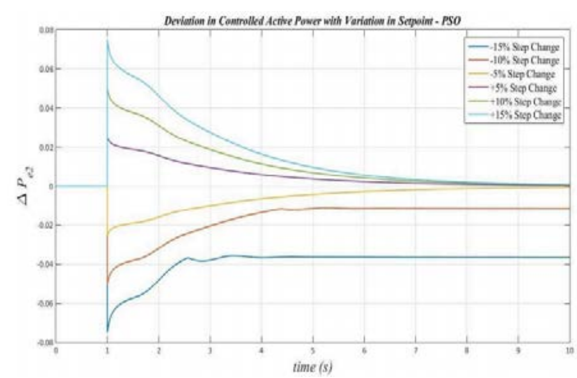

Figure 4: Deviation in line power flow ΔP_{e2} PSO tuned MIMO control system under variation of power flow setpoint.

There are two observations that can be made from figures (3) and (4), the first is that for setpoints -15% to -5% of the initial line active power flow there is a steady state error which can be seen in both control systems. Hence, this is an issue of the control system structure, and specifically the pairing of inputs and outputs. Where the active power flow P_{e2} is controlled through the amplitude modulation index of the boosting converter m_B, where $0 \leq m_B \leq 2$ p.u based on [15]. Due to this the control signal gets saturated when the value of the setpoint is varied in the negative region. The other observation that can be seen, is that the response of the BBO tuned control system for power flow control is superior to that of the PSO tuned control system when comparing the settling time of the output.

4.2 Power System Oscillation Damping

This is to evaluate the ability of the obtained control systems to damp power system oscillations resulting from different type of disturbances that can occur in power systems. In this section the control system will be subjected to two types of disturbances:

4.2.1 Generator Load Variation:

A common occurrence disturbance in the system is the load variation that causes the input mechanical power of the generator to vary in accordance to that variation. The UPFC power oscillation damping controller of the multivariable controller is designed in order to mitigate the system oscillations that are resulting from these variations. In this test both of the controllers are subjected to a 10% step disturbance in the mechanical power P_m under light and nominal loading conditions of the generator.

Table 2: System eigenvalues and EM damping ratios for light and nominal loading condition.

	BBO	PSO
Light	EM= -1.0750±j5.1840	EM= -2.0042±j6.0193
ζ	0.2030	0.2240
Nominal	EM= -1.3237±j5.7602	EM= -2.1394±j7.1600
ζ	0.3159	0.2863

Table 2, gives the electromechanical modes and their respective damping ratio. It can be seen that the PSO tuned control system has superior damping capability when compared to the BBO tuned control system.

[Case 1: Light Loading ($P_e = 0.3$ p.u, $Q_e = 0.015$ p.u)]

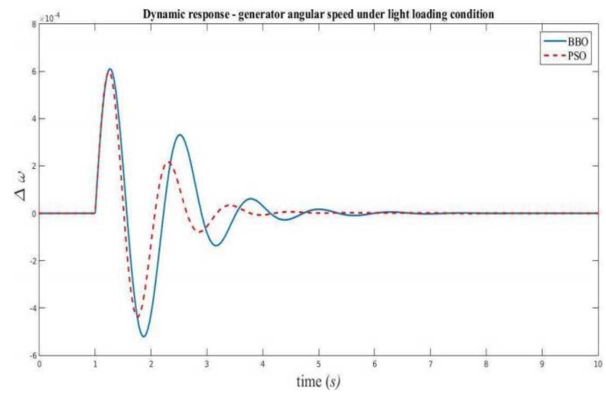

Figure 5: Deviation in rotor angular speed $\Delta\omega$ under light loading conditions for a 10% step change in P_m.

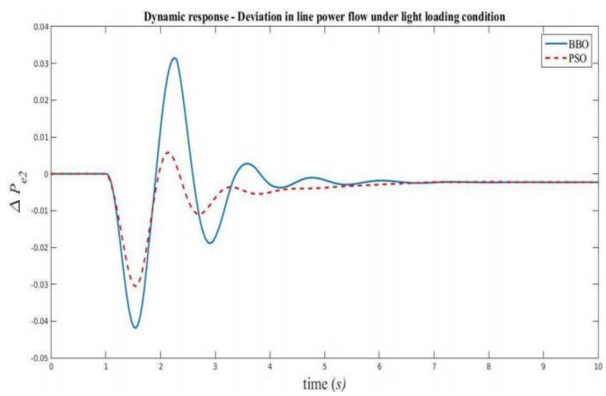

Figure 6: Deviation in active power flow ΔP_{e2} under light loading conditions for a 10% step change in P_m.

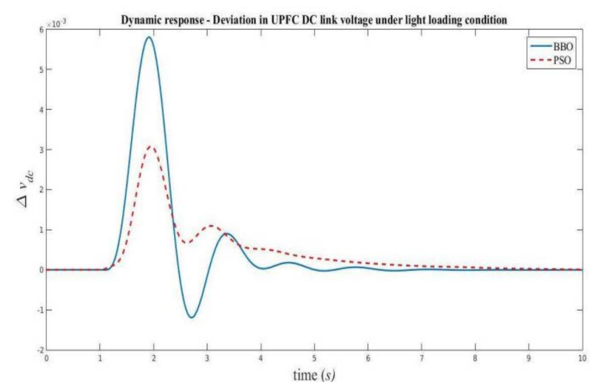

Figure 7: Deviation in UPFC DC voltage Δv_{dc} under light loading conditions for a 10% step change in P_m.

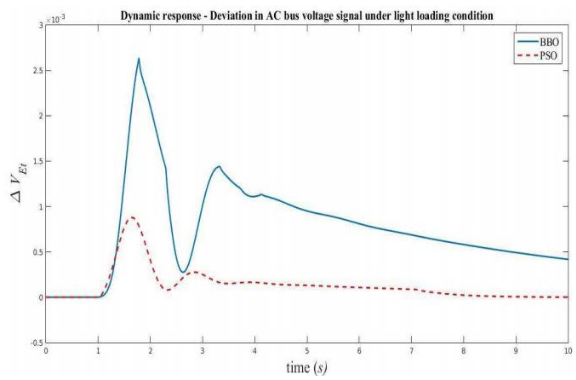

Figure 8: Deviation in UPFC bus voltage ΔV_{Et} under light loading conditions for a 10% step change in P_m.

Figures 5 to 8 draws the same conclusion as table II, where it can be observed that for the PSO tuned control system the performance is superior in terms of the settling time and the overshoot for this type of disturbance. It can be noted also that for the deviation in active power flow that there is a steady state error, and that has been outlined in the prior study case.

[Case 2: Nominal Loading (P_e = 1.0 p.u, Q_e =0.015 p.u)]

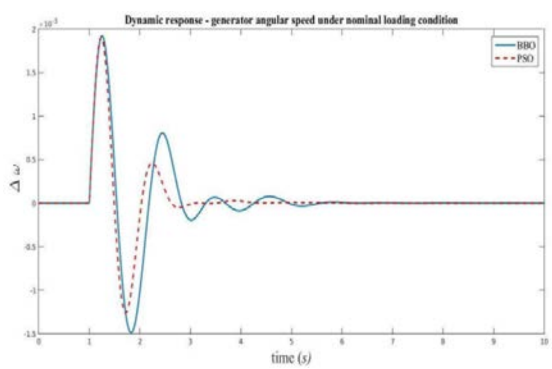

Figure 9: Deviation in rotor angular speed $\Delta\omega$ under nominal loading conditions for a 10% step change in P_m.

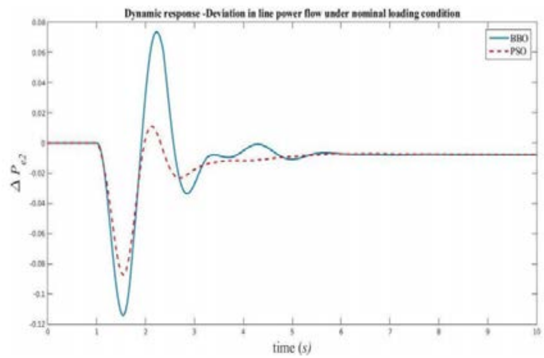

Figure 10: Deviation in active power flow ΔP_{e2} under nominal loading conditions for a 10% step change in P_m.

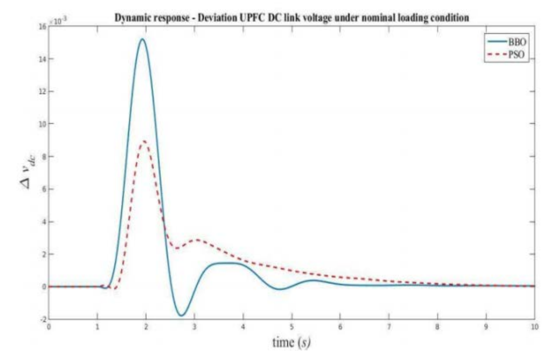

Figure 11: Deviation in UPFC DC voltage Δv_{dc} under nominal loading conditions for a 10% step change in P_m.

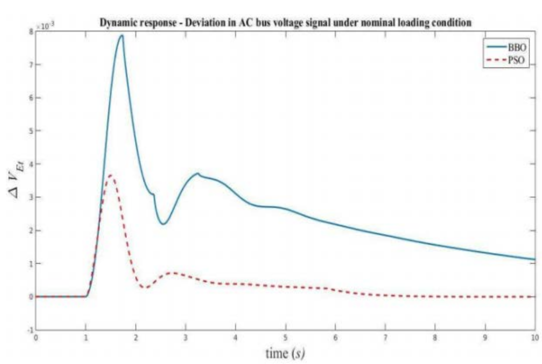

Figure 12: Deviation in UPFC bus voltage ΔV_{Et} under nominal loading conditions for a 10% step change in P_m.

Similar results were expected at nominal loading as was in the light loading, and it c an be confirmed through figures 9 to 12. The performance of PSO tuned controller is better in terms of damping system oscillations.

4.2.2 Three Phase Fault at Generator Bus

As well as for the common occurrence disturbance, the UPFC multivariable controller must operate satisfactorily under sever conditions following a fault in the system in order to bring the system back to its stable equilibrium operating point. In this test a three phase six cycle short circuit fault is simulated at the generating bus and the performance of the control systems are investigated. The fault introduced here for heavy loading and leading power factor conditions. The electromechanical modes and damping ratios are given in table 3 below:

Table 3: System eigenvalues and EM damping ratios for heavy and leading power factor conditions.

	BBO	PSO
Heavy	EM= -1.4010±*j*6.4113	EM= -1.9993±*j*7.9931
ζ	0.2135	0.2427
Leading	EM= -1.2218±j5.4152	EM= -2.1529±j6.5935
ζ	0.2201	0.3104

[Case 1:Heavy Loading (P_e = 1.1 p.u, Q_e = 0.4p.u)]

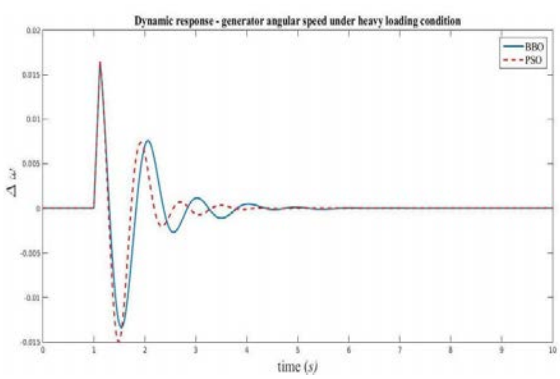

Figure 13: Deviation in rotor angular speed Δω under heavy loading for a 6 cycle three phase fault at generator bus.

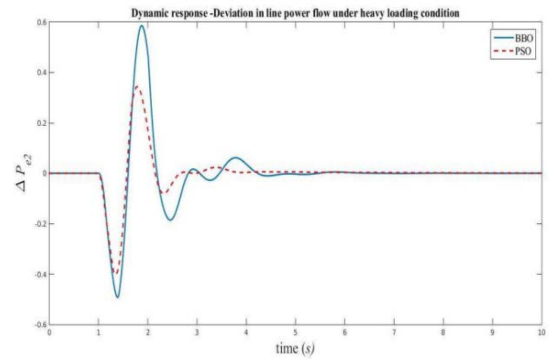

Figure 14: Deviation in active power flow ΔP_{e2} under heavy loading for a 6 cycle three phase fault at generator bus.

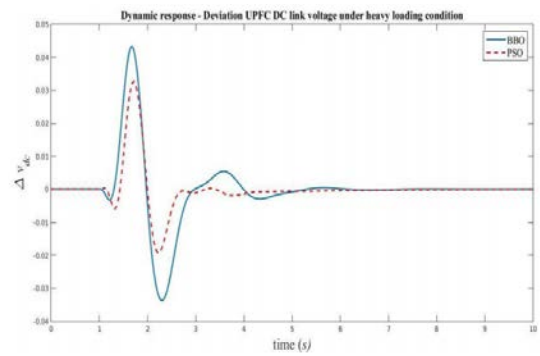

Figure 15: Deviation in UPFC DC voltage Δv_{dc} under heavy loading for a 6 cycle three phase fault at generator bus.

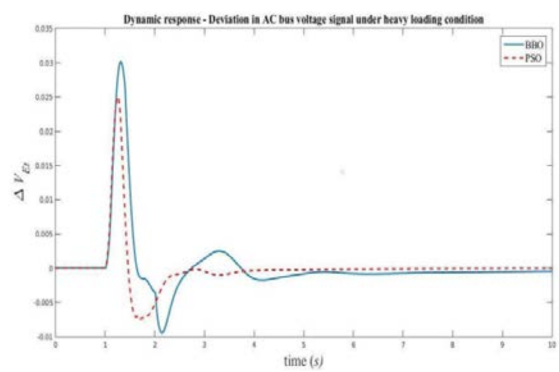

Figure 16: Deviation in UPFC Bus voltage ΔVEt under heavy loading for a 6 cycle three phase fault at generator bus.

[Case 2:Leading Power Factor (P_e = 0.7 p.u , Q_e = -0.03 p.u)]

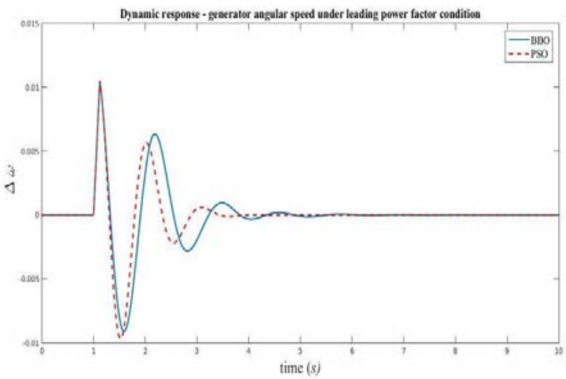

Figure 17: Deviation in rotor angular speed $\Delta\omega$ under leading power factor for a 6 cycle three phase fault at generator bus.

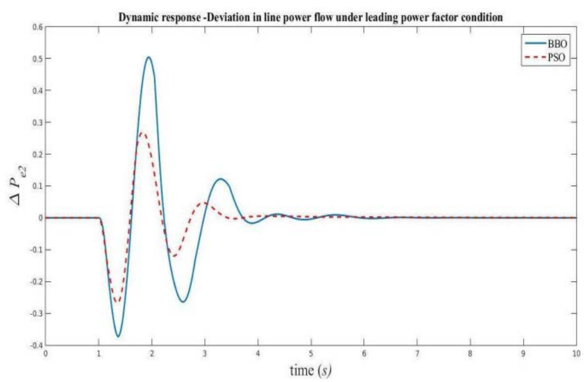

Figure 18: Deviation in active power flow ΔP_{e2} under leading power factor for a 6 cycle three phase fault at generator bus.

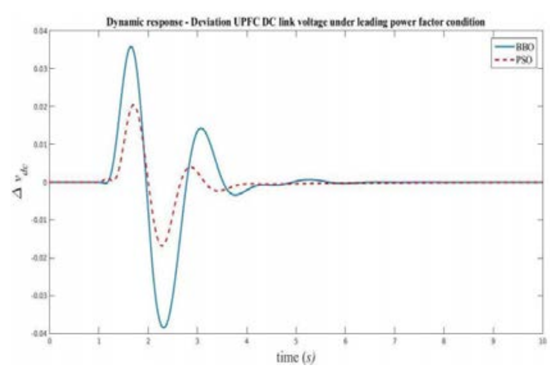

Figure 19: Deviation in UPFC DC voltage Δv_{dc} under leading power factor for a 6 cycle three phase fault at generator bus.

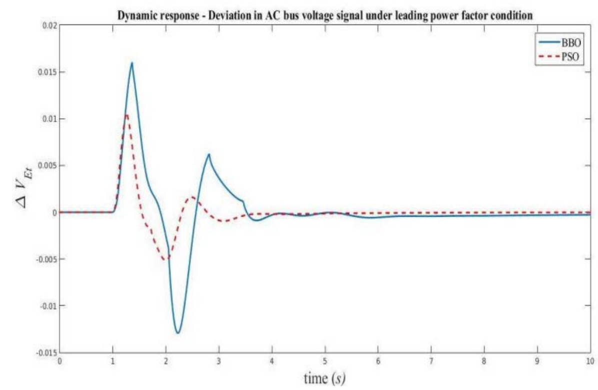

Figure 20: Deviation in UPFC Bus voltage ΔV_{Et} under leading power factor for a 6 cycle three phase fault at generator bus.

Similar to the case of the step change in generator load, it can be seen from figures (13) to (20) that the PSO tuned control system is far better in damping the oscillations when compared to the BBO tuned control system, in terms of settling time, overshoot and the steady state error which can be seen in figures (16) and (20) for the deviation in UPFC bus voltage for the BBO tuned control system.

5 Conclusions

This paper presented a co mparison study between two evolutionary optimization algorithms, namely, biogeography based optimization (BBO) and particle swarm optimization (PSO), in designing a multivariable controller for the UPFC. The control system designed was intended to: 1) control the active power flow in the transmission line, 2) damp power system oscillations, 3) regulate the UPFC bus voltage, and 4) regulate UPFC DC voltage. The design of the different controllers was simultaneously through the introduction of a weighted sum of the integral time absolute error (ITAE) performance index for each controlled output. The two algorithms evaluated the time based objective function that is to be minimized, where it w as found that PSO tuned control system had achieved a lower value of the objective function. In addition, the obtained control systems with optimal parameters from each algorithms were test for various system disturbances such as: variation of active power flow setpoint and damping of power system oscillations resulting from two types of perturbations under different loading conditions.

APPENDIX

Generator Data:

$$x_d = 1;\ x_q = 0.3;\ x'_d = 0.3;\ D = 0;\ M = 10;\ T'_{d0} = 5.044;\ \omega_B = 100\pi\ rad/s;\ V_t = 1.05$$

Transmission line:

$$x_T = 0.1;\ x_{t1} = 0.6; x_{Bv} = 0.6$$

UPFC:

$$x_E = 0.1;\ x_B = 0.1;\ C_{dc} = 3;\ V_{dc} = 2;$$

REFERENCES

[1] M. Abido, “Power system stability enhancement using facts controllers: A review,” The Arabian Journal for Science and Engineering, vol. 34,no. 1B, pp. 153–172, 2009.

[2] L. Gyugyi, “Unified power-flow control concept for flexible ac transmission systems,” in IEE Proceedings C (Generation, Transmission and Distribution), vol. 139, no. 4. IET, 1992, pp. 323–331.

[3] A. Ajami, S. Hosseini, and G. Gharehpetian, “Modelling and controlling of upfc for power system transient studies,” ECTI Transactions on Electrical Eng., Electronics, and Communications, vol. 5, no. 2, pp. 29–35, 2007.

[4] A. Nabavi-Niaki and M. Iravani, “Steady-state and dynamic models of unified power flow controller (upfc) for power system studies,” Power Systems, IEEE Transactions on, vol. 11, no. 4, pp. 1937–1943, Nov 1996.

[5] H. Wang and Q. Wu, “Multivariable design of a multiple-functional unified power flow controller,” in Power Engineering Society Summer Meeting, 2000. IEEE, vol. 3, 2000, pp. 1363–1368 vol. 3.

[6] H. Wang, “Interactions and multivariable design of multiple control functions of a unified power flow controller,” International journal of electrical power & energy systems, vol. 24, no. 7, pp. 591–600, 2002.

[7] H. Wang, M. Jazaeri, and Y. Cao, “Analysis of control conflict between upfc multiple control functions and their interaction indicator,” International J. of Control, Automation, and System, vol. 3, no. 2, pp. 315–321, 2005.

[8] S. A. Taher, S. Akbari, A. Abdolalipour, and R. Hematti, “Robust decentralized controller design for upfc using μ-synthesis,” Communications in Nonlinear Science and Numerical Simulation, vol. 15, no. 8, pp. 2149–2161, 2010.

[9] S. A. Taher, R. Hemmati, A. Abdolalipour, and S. Akbari, “Comparison of different robust control methods in design of decentralized {UPFC} controllers,” International Journal of Electrical Power & Energy Systems, vol. 43, no.1,pp.173 – 184, 2012. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0142061512001524

[10] S. A. Taher and M. Karim Amooshahi, “Optimal placement of upfc in power systems using immune algorithm,” Simulation Modelling Practice and Theory, vol. 19, no. 5, pp. 1399–1412, 2011.

[11] S. Panda and N. P. Padhy, “Matlab/simulink based model of singlemachine infinite-bus with tcsc for stability studies and tuning employing ga.” International Journal of Computer Science & Engineering, vol. 1, no. 1, 2007.

[12] H. Shayeghi, H. Shayanfar, S. Jalilzadeh, and A. Safari, “Design of output feedback upfc controller for damping of electromechanical oscillations using pso,” Energy Conversion and Management, vol. 50, no. 10, pp. 2554–2561, 2009.

[13] H Shayeghi, HA Shayanfar, S Jalilzadeh, “Coa based robust output feedback upfc controller design,” Energy Conversion and Management, vol. 51, no. 12, pp. 2678–2684, 2010.

[14] A. Ajami and R. Gholizadeh, “Optimal design of upfc-based damping controller using imperialist competitive algorithm,” Turkish Journal of Electrical Engineering & Computer Sciences, vol. 20, no. Sup. 1, pp. 1109–1122, 2012.

[15] A. T. Al-Awami, Y. Abdel-Magid, and M. Abido, “A particle-swarmbased approach of power system stability enhancement with unified power flow controller,” International Journal of Electrical Power & Energy Systems, vol. 29, no. 3, pp. 251–259, 2007.

[16] A. T. Al-Awami, M. A. Abido, and Y. L. Abdel-Magid, “Application of pso to design upfc-based stabilizers.

[17] M. A. Abido, A. Al-Awami, and Y. Abdel-Magid, “Analysis and design of upfc damping stabilizers for power system stability enhancement,” in Industrial Electronics, 2006 IEEE International Symposium on, vol. 3, July 2006, pp. 2040–2045.

[18] H. Wang, “A unified model for the analysis of facts devices in damping power system oscillations. iii. unified power flow controller,” Power Delivery, IEEE Transactions on, vol. 15, no. 3, pp. 978–983, Jul 2000.

[19] D. Simon, “Biogeography-based optimization,” Evolutionary Computation, IEEE Transactions on, vol. 12, no. 6, pp. 702–713, 2008.

[20] J. Kennedy, R. Eberhart et al., “Particle swarm optimization,” in Proceedings of IEEE international conference on neural networks, vol. 4, no. 2. Perth, Australia, 1995, pp. 1942–1948.

[21] X.-S. Yang, Engineering optimization: an introduction with metaheuristic applications. John Wiley & Sons, 2010.

[22] M. Clerc and J. Kennedy, "The particle swarm-explosion, stability, and convergence in a multidimensional complex space," Evolutionary Computation, IEEE Transactions on, vol. 6, no. 1, pp. 58–73, 2002.
[23] J. F. Kennedy, J. Kennedy, and R. C. Eberhart, Swarm intelligence. Morgan Kaufmann, 2001.
[24] R. C. Eberhart and Y. Shi, "Comparing inertia weights and constriction factors in particle swarm optimization," in Evolutionary Computation, 2000. Proceedings of the 2000 Congress on, vol. 1. IEEE, 2000, pp.84–88.