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Optimal Design of UPFC Controller for Damping Power System Oscillations by Using Bacterial Foraging Algorithm

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Abstract: This paper presents an approach for designing Unified Power Flow Controller (UPFC) using Bacterial Foraging Algorithm (BFA) for damping low frequency oscillations in a power system. The problem of UPFC-based damping controller is formulated as an optimization problem according to the eigen value-based objective function comprising the damping factor, and the damping ratio of the un-damped electromechanical modes to be solved using Bacteria Foraging Algorithm (BFA). To ensure the robustness of the proposed stabilizers, the design process takes into account a wide range of operating conditions. The effectiveness of the new controller is demonstrated through eigenvalue analysis and time-domain simulation studies show that the proposed controller has an excellent capability in damping power system oscillations.

Key words: Power system, BFA, damping oscillation, UPFC

INTRODUCTION

In the past, most control of power systems was aided by mechanical devices and actions. This came at the expense of providing greater operating margins and redundancies. The rapid development of power electronics has made it possible to design power electronic equipment of high rating for high voltage systems. The voltage stability problem resulting from transmission system and cheap power transfer may be, at least partly, improved by using of the equipment well-known as flexible AC Transmission Systems (FACTS) controllers.

FACTS devices can reduce the flows of heavily loaded lines, maintain the bus voltage at desired level, and improve the stability of the power network. Unified power flow controller (UPFC) is a versatile FACT device which can independently or simultaneously control the active power, the reactive power, and the bus voltage to which it is connected (Keri *et al.*, 1998; Al-Awami *et al.*, 2007; Tambey and Kothari, 2003).

UPFC is one of the most important FACTS devices since it can provide various types of compensation voltage regulation, phase shifting regulation, impedance compensation and reactive compensation. The unique feature of UPFC is its capability for independent control of real and reactive power flows in the transmission system (Gyugyi, 1992). The application of the UPFC to The modern power system can therefore lead to the more flexible, secure and economic operation (Hingorani and Gyugyi, 1999).

In this paper, a Single Machine Infinite Bus (SMIB) power system installed with a UPFC is considered as the case study and BFA is used to design UPFC controller parameters. The problem of the controller design is formulated as an optimization problem and BFA is used to solve it. The effectiveness of the proposed controller is demonstrated through simulation results and eigenvalues analysis for a wide range of operating conditions and disturbances.

MATERIALS AND METHODS

Bacterial Foraging Algorithm (BFA):

The idea of BFA is based on the fact that natural selection tends to eliminate animals with poor foraging strategies and favor those having successful foraging strategies. After many generations, poor foraging strategies are either eliminated or reshaped into good ones. The E.coli bacteria that are present in our intestines have a foraging strategy governed by four processes, namely, chemotaxis, swarming, reproduction, and elimination and dispersal (Passino, 2002).

Chemotaxis:

This process is achieved through swimming and tumbling. Depending upon the rotation of the flagella in

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Corresponding Author: Saeid Jalilzadeh, Department of Electrical Engineering, Faculty of Engineering, Zanjan University, Zanjan, Iran each bacterium, it decides whether it should move in a predefined direction (swimming) or an altogether different direction (tumbling), in the entire life time of the bacterium.

To represent a tumble, a unit length random direction, say, $\phi(j)$ is generated; this will be used to define the direction of movement after a tumble.
In particular:

$$\theta^i(j+1,k,l) = \theta^i(j,k,l) + C(i)\phi(j) \tag{1}$$

Where $\theta^i(j,k,l)$ represents the *i*th bacterium at *j*th chemotactic, *k*th reproductive, and *l*th elimination and dispersal step. *C(i)* is the size of the step taken in the random direction specified by the tumble (run length unit).

Swarming:

During the process of reaching toward the best food location, it is always desired that the bacterium which has searched the optimum path should try to provide an attraction signal to other bacteria so that they swarm together to reach the desired location. In this process, the bacteria congregate into groups and, hence, move as concentric patterns of groups with high bacterial density. The mathematical representation for swarming can be represented by:

$$\begin{aligned} J_{cc}(\theta,P(j,k,l)) &= \sum_{i=1}^{S} J_{cc}^{i}(\theta,\theta^i(j,k,l)) \\ &= \sum_{i=1}^{S}\left[-d_{attract}\exp(-\omega_{attract}\sum_{m=1}^{p}(\theta_m-\theta_m^i)^2)\right] \\ &= \sum_{i=1}^{S}\left[h_{repellent}\exp(-\omega_{repellent}\sum_{m=1}^{p}(\theta_m-\theta_m^i)^2)\right] \end{aligned} \tag{2}$$

where $J_{cc}(\theta,P(j,k,l))$ is the cost function value to be added to the actual cost function to be minimized to present a time varying cost function. "*S*" is the total number of bacteria. "*P*" is the number of parameters to be optimized that are present in each bacterium. $d_{attract}$, $\omega_{attract}$, $h_{repelent}$ and $\omega_{repelent}$ are different coefficients that are to be chosen judiciously.

Reproduction:

The least healthy bacteria die, and the other healthiest bacteria each split into two bacteria, which are placed in the same location. This makes the population of bacteria constant.

Elimination and Dispersal:

It is possible that in the local environment, the life of a population of bacteria changes either gradually by consumption of nutrients or suddenly due to some other influence. Events can kill or disperse all the bacteria in a region. They have the effect of possibly destroying the chemotactic progress, but in contrast, they also assist it, since dispersal may place bacteria near good food sources. Elimination and dispersal helps in reducing the behavior of stagnation (i.e., being trapped in a premature solution point or local optima). The detailed mathematical derivations as well as theoretical aspect of this new concept are presented in (Passino, 2002; Mishra, 2005).

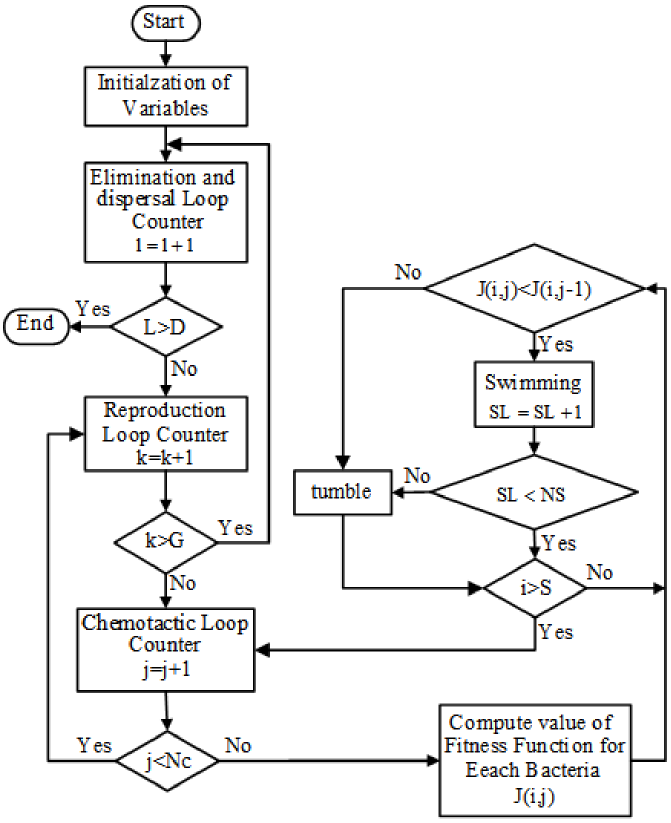


Fig. 1: Flowchart of bacteria foraging algorithm.

Case Study System:

Figure 1 shows a Single Machine Infinite Bus (SMIB) power system equipped with a UPFC. The synchronous generator is equipped with a PSS and it is delivering power to the infinite-bus through a double circuit transmission line.

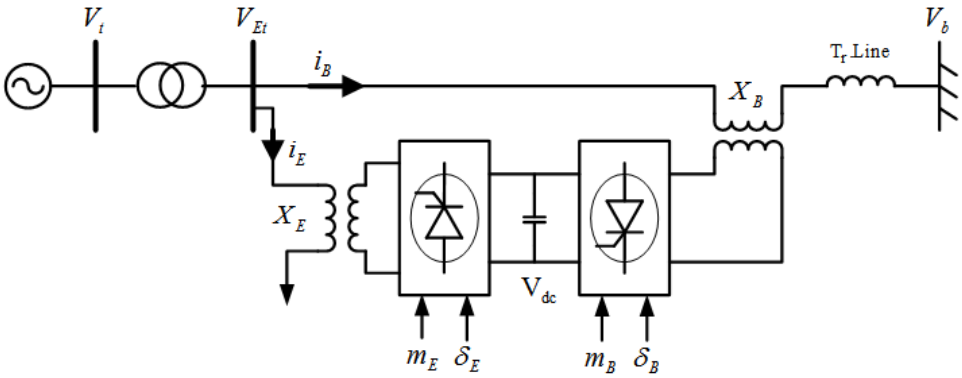


Fig. 2: SMIB power system equiped with UPFC.

Power System Nonlinear Model with UPFC:

The dynamic model of the UPFC is required in order to study the effect of the UPFC for enhancing the small signal stability of the power system. The system data is given in the (Wang, 1999; Dash *et al*., 2000; Wang, 2002). By applying Parks transformation and neglecting the resistance and transients of the ET and BT transformers, the UPFC can be modeled as:

$$V_E = \frac{m_E v_{dc}}{2} e^{j\delta_E} \;\; ; \;\; V_B = \frac{m_B v_{dc}}{2} e^{j\delta_B} \tag{3}$$

$$\begin{bmatrix} v_{Etd} \\ v_{Etq} \end{bmatrix} = \begin{bmatrix} 0 & -x_E \\ x_E & 0 \end{bmatrix} \begin{bmatrix} i_{Ed} \\ i_{Eq} \end{bmatrix} + \begin{bmatrix} \dfrac{m_E \cos\delta_E v_{dc}}{2} \\ \dfrac{m_E \sin\delta_E v_{dc}}{2} \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} v_{Btd} \\ v_{Btq} \end{bmatrix} = \begin{bmatrix} 0 & -x_B \\ x_B & 0 \end{bmatrix} \begin{bmatrix} i_{Bd} \\ i_{Bq} \end{bmatrix} + \begin{bmatrix} \dfrac{m_B \cos\delta_B v_{dc}}{2} \\ \dfrac{m_B \sin\delta_B v_{dc}}{2} \end{bmatrix} \tag{5}$$

$$\dot{v}_{dc} = \frac{3m_E}{4C_{dc}}[\cos\delta_E \quad \sin\delta_E] \begin{bmatrix} i_{Ed} \\ i_{Eq} \end{bmatrix} + \frac{3m_B}{4C_{dc}}[\cos\delta_B \quad \sin\delta_B] \begin{bmatrix} i_{Bd} \\ i_{Bq} \end{bmatrix} \tag{6}$$

Where v_{Et} , i_{Et} , v_{Bt} and i_B are the excitation voltage, excitation current, boosting voltage, and boosting current, respectively; C_{dc} and v_{dc} are the DC link capacitance and voltage, respectively.

The non-linear model of the SMIB system of fig. 1 is:

$$\dot{\delta} = \omega_b(\omega - 1) \tag{7}$$

$$\dot{\omega} = (P_m - P_e - D\Delta\omega)/M \tag{8}$$

$$\dot{E}'_q = (E_{fd} - (x_d - x'_d)i_d - E'_q)/T'_{do} \tag{9}$$

$$\dot{E}_{fd} = (-E_{fd} + K_a(V_{ref} - V +_t U_{PSS}))/T_a \tag{10}$$

Table 1: System parameters

Generator	$M = 8\text{MJ/MVA}$, $X_q = 0.6$ pu , $T'_{do} = 5.044$ s , $X_d = 1$ pu , $X'_d = 0.3$ pu , $D = 0$
Excitation system	$K_a = 10,\ T_a = 0.05$ s
Transformers	$X_r = 0.1$ pu , $X_E = 0.1$ pu , $X_B = 0.1$ pu
Transmission line	$X_L = 1$ pu
Operating condition	$P = 0.8$ pu , $V_b = 1$ pu , $V_t = 1$ pu
DC link parameter	$V_{dc} = 2$ pu , $C_{dc} = 1$ pu
UPFC parameter	$m_B = 0.08$, $\delta_B = -78.21^\circ$, $m_E = 0.4$, $\delta_E = -85.35^\circ$, $K_s = 1$, $T_s = 0.05$

Power System Linearized Model:

The linearized model of power system shown in fig. 1 is given in (Al-Awami *et al.*, 2007; Tambey and Kothari, 2003). The state-space model of power system is given by:

$$\dot{X} = AX + BU \tag{11}$$

Where, the state vector x, control vector u, A and B are:

$$x = [\Delta\delta \quad \Delta\omega \quad \Delta E'_q \quad \Delta E_{fd} \quad \Delta v_{dc}] \tag{12}$$

$$u = \left[\Delta m_E \quad \Delta\delta_E \quad \Delta m_B \quad \Delta\delta_E\right]^T \tag{13}$$

$$A = \begin{bmatrix} 0 & \omega_0 & 0 & 0 & 0 \\ \frac{-K_1}{M} & 0 & \frac{-K_2}{M} & 0 & \frac{-K_{pd}}{M} \\ \frac{-K_4}{T'_{do}} & 0 & \frac{-K_3}{T'_{do}} & \frac{1}{T'_{do}} & \frac{-K_{qd}}{T'_{do}} \\ \frac{-K_A K_5}{T_A} & 0 & \frac{-K_A K_6}{T_A} & \frac{1}{T_A} & \frac{-K_A K_{vd}}{T_A} \\ K_7 & 0 & K_8 & 0 & -K_9 \end{bmatrix} \tag{14}$$

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 \\ \frac{-K_{pe}}{M} & \frac{-K_{p\delta e}}{M} & \frac{-K_{pb}}{M} & \frac{-K_{p\delta b}}{M} \\ \frac{-K_{qe}}{T'_{do}} & \frac{-K_{q\delta e}}{T'_{do}} & \frac{-K_{qb}}{T'_{do}} & \frac{-K_{q\delta b}}{T'_{do}} \\ \frac{-K_A K_{ve}}{T_A} & \frac{-K_A K_{v\delta e}}{T_A} & \frac{-K_A K_{vb}}{T_A} & \frac{-K_A K_{v\delta b}}{T_A} \\ K_{ce} & K_{c\delta e} & K_{cb} & K_{c\delta b} \end{bmatrix} \tag{15}$$

The block diagram of the linearized dynamic model of the SMIB power system with UPFC is shown in Fig. 3.

UPFC-based Damping Controller:

The damping controllers are designed to produce an electrical torque in phase with the speed deviation according to phase compensation method. The four control parameters of the UPFC (m_B, m_E, δ_B and δ_E) can be modulated in order to produce the damping torque. In this paper δ_E and m_B are modulated in order to damping controller design (Shayeghi *et al.*, 2009). The structure of UPFC-based damping controller is shown in Fig. 4. It comprises gain block, signal-washout block and lead-lag compensator.

In this work, an Integral of Time multiplied Absolute value of the Error is taken as the objective function. The objective function is defined as follows:

$$Minimize: \ J = \int_0^{t_{sim}} t\left|\Delta\omega\right| dt \tag{16}$$

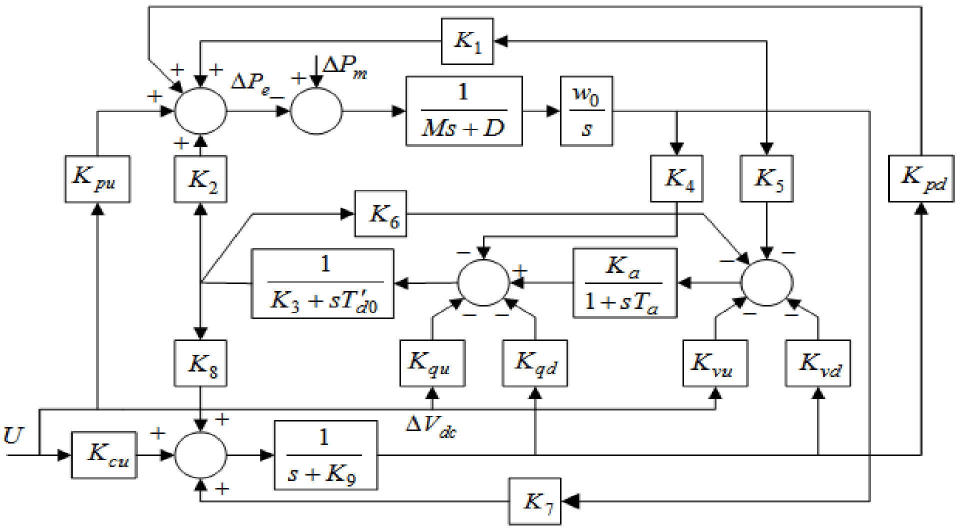


Fig. 3: Modified Heffron-Philips transfer function model.

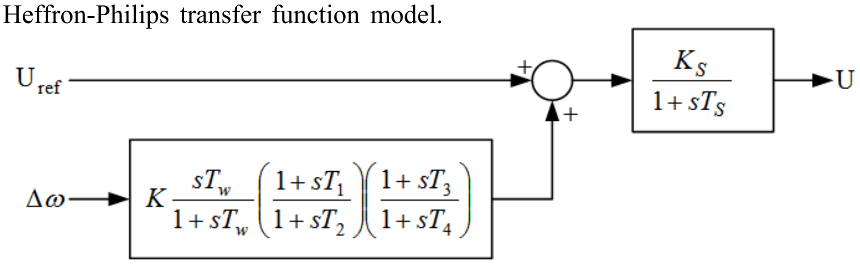


Fig. 4: UPFC with lead-lag controller.

In the above equations, t_{sim} is the time range of simulation. The design problem can be formulated as the following constrained optimization problem, where the constraints are the controller parameters bounds:

$$\begin{aligned} & K^{\min} \le K \le K^{\max} \\ & T_1^{\min} \le T_1 \le T_1^{\max} \\ & T_2^{\min} \le T_2 \le T_2^{\max} \\ & T_3^{\min} \le T_3 \le T_3^{\max} \\ & T_4^{\min} \le T_4 \le T_4^{\max} \end{aligned} \tag{17}$$

Typical ranges of the optimized parameters are [0.01-100] for K and [0.01-1] for T_1 , T_2 , T_3 and T_4. Considering the objective functions given in (16), the proposed approach employs BFA to solve this optimization problem and search for an optimal set of controller parameters.

RESULTS AND DISCUSSIONS

Design of Damping Controller:

The Bacterial Foraging Algorithm has been applied to search for the optimal parameter settings of each of the supplementary controllers. The final parameter settings of the controllers are given in Table 2.

Table 2: The optimal parameter setting of controller

controller Parameter	δ_E	m_b
K	97.6700	100
T_1	1.0000	0.9806
T_2	0.4878	0.6855
T_3	0.4182	0.7162
T_4	0.6187	0.7300

Eigen Value Analysis:

The system eigenvalues with and without the proposed controllers at nominal condition are given in Table 3. It is clear that the open loop system is unstable but the proposed controllers stabilize the system. It is obvious that the electromechanical mode eigenvalues have been shifted to the left in s-plane and the system damping is greatly improved.

Table 3: System eigen values (nominal condition)

Non controller	δ_E	m_b
-96.5814	-96.5718	-96.5668
0.1108 ±6.9121i	-4.6304 ± 4.2140i	-4.3499± 3.6104i
-2.9426±0.1514i	-1.8821 ± 0.3116i	-1.3833
	-3.0474 ± 0.2222i	-1.5638
		-3.8415, -3.1228

Time Domain Simulation:

The performance of the proposed controller under transient conditions is verified by applying a 6-cycle disturbance at t =1 sec, at the middle of the one transmission line. The disturbance is cleared by permanent tripping of the faulted line. It can be inferred that the UPFC based damping controller provide satisfactory dynamic performance at the nominal operating condition with objective function. It is extremely important to investigate the effect of variation of the loading condition on the dynamic performance of the system. The operating conditions are shown in table 4.

Table 4: Value of parameters for APSO

	Value		
Case	P	P	X_L
Nominal load	0.8 pu	0.114 pu	0.3 pu
Light load	1.2 pu	0.4 pu	0.3 pu
Heavy load	0.2 pu	0.01 pu	0.3 pu

Fig. 5 shows the system dynamic response for a six cycle fault disturbance for rotor speed variation. The speed deviation of generator at nominal, heavy and light loading conditions due to designed controller based on the δ_B and m_B are shown in Fig. 6. It is clearly seen that the responses are hardly affected in terms of settling time following wide variations in loading condition.

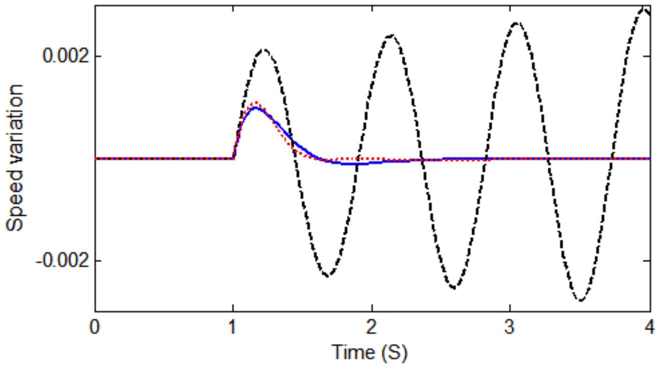
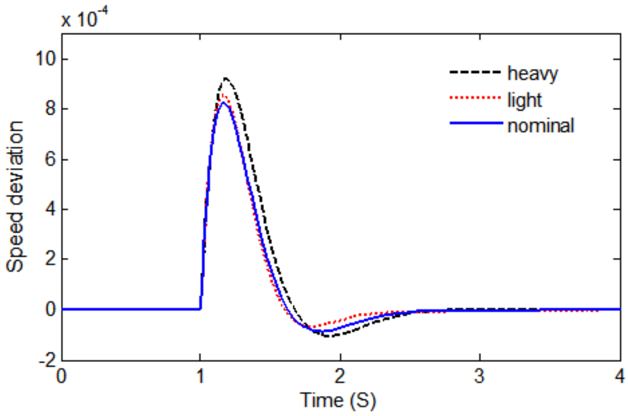


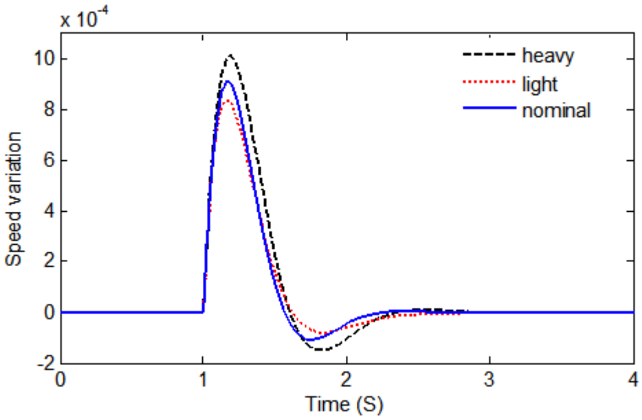
Fig. 5: Dynamic responses for Δω at nominal loading; solid (m_B controller), Dot (δ_E controller), Dashed (non controller).

Conclusion:

The Bacterial Foraging Algorithm has been applied to the design of UPFC based damping controller. An optimization technique has been proposed to design the UPFC controller individually. The stabilizers are tuned to simultaneously shift the undamped electromechanical modes of the machine to a prescribed zone in the s-plane. BFA has been utilized to search for the optimal controller parameters. The eigenvalues analysis and simulation results show that the proposed controller has good performance on damping low frequency oscillations and improves the transient stability under different operating conditions.



(A)



(B)

Fig. 6: System dynamic responses for a 6-cycle disturbance with nominal, light and heavy loading for speed variation; (a) m_B controller, (b) δ_E controller.

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