UNIFIED POWER FLOW CONTROLLER DESIGN FOR POWER SYSTEM STABILITY ENHANCEMENT VIA BACTERIA FORAGING OPTIMIZATION ALGORITHM

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Abstract: *Social foraging behavior of Escherichia coli bacteria has recently been explored to develop a novel algorithm for distributed optimization and control. The Bacterial Foraging Optimization Algorithm (BFOA), as it is called now, is currently gaining popularity in the community of researchers, for its effectiveness in solving certain difficult real-world optimization problems. This paper proposes BFOA based Unified Power Flow Controller (UPFC) for the suppression of oscillations in power system. The proposed design problem of UPFC over a wide range of loading conditions and system configurations is formulated as an optimization problem with an eigenvalue based objective function. Moreover, supplementary damping controller is superimposed on UPFC to enhance the suppression of these oscillations. BFOA is employed to search for optimal controllers parameters. The proposed controllers are tested on a power system. The nonlinear simulation results and eigenvalue analysis show the effectiveness and robustness of the proposed approach over a wide range of loading conditions and system parameters variations.*

Keywords: *Bacteria Foraging, Power System Stability, Supplementary damping controller, UPFC.*

1. Introduction

The power transfer in an integrated power system is constrained by transient stability, voltage stability and small signal stability. These constraints limit a full utilization of available transmission corridors. Flexible AC Transmission System (FACTS) is the technology that provides the needed corrections of the transmission functionality in order to fully utilize the existing transmission facilities and hence, minimizing the gap between the stability limit and thermal limit [1].

UPFC is one of the FACTS devices, which can control power system parameters such as terminal voltage, line impedance and phase angle. Therefore, it can be used not only for power flow control, but also for power system stabilizing control. A modified linearised Heffron-Phillips model of a power system installed with UPFC is presented in [2]. A multifunctional FACTS controller opens up new opportunities for controlling power and enhancing the usable capacity of present, as well as new and upgraded lines [3]. A UPFC supplementary damping controller is presented in [4] for damping the electromechanical mode of oscillations. In [5] systematic design of four alternative UPFC damping controllers are presented.

Recently, global optimization technique like Genetic Algorithm (GA), has attracted the attention in the field of controller parameter optimization [6]. Unlike other techniques, GA is a population based search algorithm, which works with a population of strings that represent different solutions. Therefore, GA has implicit parallelism that enhances its search capability and the optima can be located swiftly when applied to complex optimization problems. Unfortunately recent research has identified some deficiencies in GA performance [7]. This degradation in efficiency is apparent in applications with highly *epistatic* objective functions (i.e. where parameters being optimized are highly correlated). Also, the premature convergence of GA degrades its performance and reduces its search capability.

BFOA is proposed as a solution to the above-mentioned problems and drawbacks [8]. Moreover, BFOA due to its unique dispersal and elimination technique can find favorable regions when the population involved is small. These unique features of the algorithms overcome the premature convergence problem and enhance the search capability. Hence, it is suitable optimization tool for power system controllers.

This paper proposes a new optimization algorithm known as Bacterial Foraging (BF) based UPFC for damping of power system electromechanical oscillations. BFOA is used for tuning the UPFC controller parameter when it acts alone and with superimposed auxiliary damping controller. A comparison between UPFC controller and UPFC supplementary damping controller is discussed. An eigenvalue based objective function reflecting the combination of damping factor and damping ratio, is optimized for different operating conditions. The effectiveness of these controllers are supported by the results observed in simulations, which show the ability of these controllers in damping oscillations over a wide range of loading conditions and system parameters. Also, these results validate the superiority of using UPFC supplementary damping controller.

2. Bacteria Foraging Optimization: A Brief Overview.

The survival of species in any natural evolutionary process depends upon their fitness criteria, which relies upon their food searching and motile behavior. The law of evolution supports those species who have better food searching ability and either eliminates or reshapes those with poor search ability. The genes of those species who are stronger gets propagated in the evolution chain since they posses ability to reproduce even better species in future generations. So a clear understanding and modeling of foraging behavior in any of the evolutionary species, leads to its application in any nonlinear system optimization algorithm. The foraging strategy of *Escherichia coli* bacteria present in human intestine can be explained by four processes, namely chemotaxis, swarming, reproduction, and elimination–dispersal [8-9].

2.1. Chemotaxis

The characteristics of movement of bacteria in search of food can be defined in two ways, i.e. swimming and tumbling together know as chemotaxis. A bacterium is said to be 'swimming' if it moves in a predefined direction, and 'tumbling' if moving in an altogether different direction. Mathematically, tumble of any bacterium can be represented by a unit length of random direction $\varphi(j)$ multiplied by step length of that bacterium $C(i)$. In case of swimming, this random length is predefined.

2.2. Swarming

For the bacteria to reach at the richest food location (i.e. for the algorithm to converge at the solution point), it is desired that the optimum bacterium till a point of time in the search period should try to attract other bacteria so that together they converge at the desired location (solution point) more rapidly. To achieve this, a penalty function based upon the relative distances of each bacterium from the fittest bacterium till that search duration, is added to the original cost function. Finally, when all the bacteria have merged into the solution point, this penalty function becomes zero. The effect of swarming is to make the bacteria congregate into groups and move as concentric patterns with high bacterial density.

2.3. Reproduction

The original set of bacteria, after getting evolved through several chemotactic stages reaches the reproduction stage. Here, best set of bacteria (chosen out of all the chemotactic stages) gets divided into two groups. The healthier half replaces with the other half of bacteria, which gets eliminated, owing to their poorer foraging abilities. This makes the population of bacteria constant in the evolution process.

2.4. Elimination and dispersal.

In the evolution process, a sudden unforeseen event can occur, which may drastically alter the smooth process of evolution and cause the elimination of the set of bacteria and/or disperse them to a new environment. Most ironically, instead of disturbing the usual chemotactic growth of the set of bacteria, this unknown event may place a newer set of bacteria nearer to the food location. From a broad perspective, elimination, and dispersal are parts of the population level long distance motile behavior. In its application to optimization, it helps in reducing the behavior of *stagnation* (i.e. being trapped in a premature solution point or local optima) often seen in such parallel search algorithms. The detailed mathematical derivations as well as theoretical aspect of this new concept are presented in [8-9].

3. System Under Study.

Fig. 1 shows a SMIB system equipped with a UPFC. The UPFC consists of an excitation transformer (ET), a boosting transformer (BT), two three-phase GTO based voltage source converters (VSCs), and a DC capacitor link. The four significant control parameters of UPFC are, m_E, m_B, δ_E, and δ_B, where m_E is the excitation amplitude modulation ratio, m_B is the boosting amplitude modulation ratio, δ_E is the excitation phase angle, and δ_B is the boosting phase angle.

Details of system data are given in appendix. The generator is represented by the third order model that comprising of the swing equations and the generator internal voltage equation. The IEEE type ST1 excitation system is used [1].

$$\dot{\delta} = \omega_B(\omega - 1) \qquad (1)$$

$$\dot{\omega} = \frac{1}{\tau_j}\left(P_m - P_e - D(\omega - 1)\right) \qquad (2)$$

where P_m and P_e are the input and output powers of the generator, respectively; τ_j and D are the inertia constant and damping coefficient, respectively; δ and ω are the rotor angle and speed, respectively; ω_B is the synchronous speed.

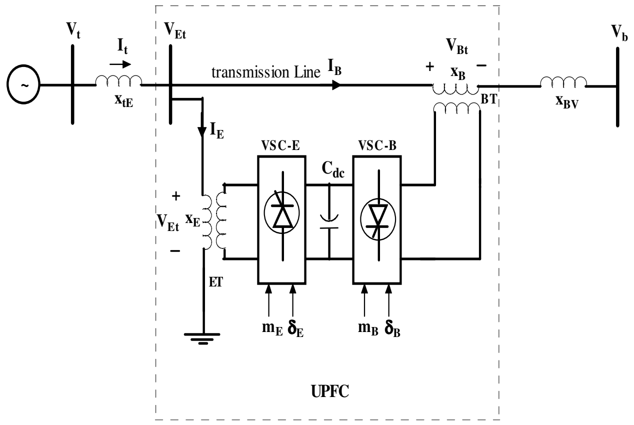

Fig. 1 System under study.

The output power of the generator can be expressed in terms of the d-axis and q-axis components of the armature current and terminal voltage as following:

$$P_e = v_d i_d + v_q i_q \tag{3}$$

The internal voltage, E'_q, equation is shown below:

$$\dot{E}'_q = \frac{-1}{\tau'_{do}} E'_q + \frac{1}{\tau'_{do}} E_{fd} + \left(\frac{X_d - X'_d}{\tau'_{do}} \right) i_d \tag{4}$$

where E_{fd} is the field voltage; τ'_{do} is the open circuit field time constant; X_d, X'_d are the d-axis reactance and d-axis transient reactance of the generator, respectively.

Also, from Fig. 1, one has

$$\bar{V}_t = jx_{tE}\bar{I}_t + \bar{V}_{Et} \tag{5}$$

$$\bar{V}_{Et} = \bar{V}_{Bt} + jx_{BV}\bar{I}_B + \bar{V}_b \tag{6}$$

The DC voltage dynamic equation is given below:

$$\frac{dV_{dc}}{dt} = \frac{3m_E}{4C_{dc}} \begin{bmatrix} \cos\delta_E & \sin\delta_E \end{bmatrix} \begin{bmatrix} I_{Ed} \\ I_{Eq} \end{bmatrix} + \frac{3m_B}{4C_{dc}} \begin{bmatrix} \cos\delta_B & \sin\delta_B \end{bmatrix} \begin{bmatrix} I_{Bd} \\ I_{Bq} \end{bmatrix} \tag{7}$$

Where I_t and V_b, are the armature current and infinite bus voltage, respectively; V_t, V_{Et}, V_{Bt}, and I_B the generator terminal voltage, ET voltage, BT voltage, and BT current, respectively; C_{dc} and V_{dc} are the DC capacitance and voltage respectively.

4. Unified Power Flow Controllers.

One of the UPFC function is to regulate its bus voltage by controlling the shunt branch output voltage from the VSC. The VSC output voltage is dependent on the amplitude modulation ratio m_E.

The bus voltage can be controlled by installing an AC voltage regulator as shown in (8).

$$m_E = K_v * (V_{E_{ref}} - V_E) \tag{8}$$

The series branch of the UPFC is used to control the power flow across the line. The phase angle is controlled as shown in (9), while the amplitude modulation index is used to control the reactive power as shown in (10).

$$\delta_B = K_p * (P_{e_{ref}} - P_e) \tag{9}$$

$$m_B = K_q * (Q_{line_{ref}} - Q_{line}) \tag{10}$$

For continuous and effective operation of a UPFC, the DC voltage across the UPFC capacitor link must be kept constant, which can be achieved by installing a DC voltage regulator as shown in (11). The DC voltage regulator functions by controlling the exchange of reactive power between the UPFC and the power system. Hence its influence upon power system oscillation damping should be expected. K_{dc} and T_{dc} are the controller gain and time constant in the converter's circuit. The block diagram of DC voltage regulator is shown in Fig. 2.

$$\delta_E = \frac{K_{dc}}{1 + sT_{dc}} * (V_{DC_{ref}} - V_{DC} + V_s) \tag{11}$$

An auxiliary damping controller is superimposed to UPFC to improve UPFC damping characteristics performance. The control signal is obtained by (12). K_{pc}, K_{ic} and T_w are the PI controller gains and wash out time constant.

$$V_S = (Kp_c + \frac{Ki_c}{s})(\frac{sT_w}{(1 + T_w s)}) * \omega \tag{12}$$

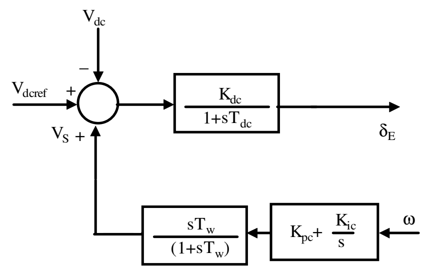

Fig. 2 Block diagram of DC regulator with auxiliary controller.

5. Objective Function.

To maintain stability and provide greater damping, the parameters of the UPFC may be selected to minimize the following objective function:

$$J_t = \sum_{j=1}^{np} \sum_{\sigma_{ij} \geq \sigma_0} (\sigma_0 - \sigma_{ij})^2 + \sum_{j=1}^{np} \sum_{\xi_{ij} \geq \xi_0} (\xi_0 - \xi_{ij})^2 \tag{13}$$

This will place the system closed-loop eigenvalues in the D shape as shown in Fig. 3.

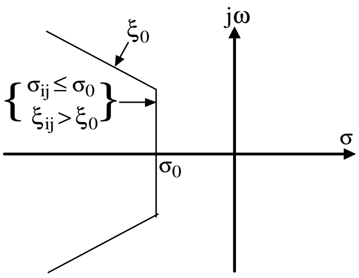

Fig. 3 A D-shape sector in the s-plane.

Where, np is the number of operating points considered in the design process, σ and ξ are the real part and the damping ratio of the eigenvalue of the operating point. In this study, σ_0 and ξ_0 are chosen to be -1.0 and 0.15 respectively [10].

6. Results and Simulations.

Table I shows the optimal values of UPFC and damping controller parameters obtained by empolying BFOA.

TABLE I
OPTIMIAL PARAMETERS OF THE PROPOSED CONTROLLERS

K_p =1.5348	K_{pc} =14.9788	K_{dc} =0.1391
K_q =-2.9178	K_{ic} =-0.7570	T_{dc} =0.05
K_v =-1.0347	T_w =1	

To assess the effectiveness and robustness of the proposed controllers, three different loading conditions given in Table II are considered without changing the controller's parameters. The eigenvalue for different controllers are presented to show the effectiveness of insertion of an auxiliary damping controller in the UPFC control system. Also, it is clear that, the open loop system is unstable because of negative damping of the electromechanical mode.

TABLE II
MECHANICAL MODES AND ξ UNDER DIFFERENT LOADING CONDITIONS AND CONTROLLERS.

	Light load	Normal load	Heavy load
No controller	-0.46 ± 9.62j 0.0436	-0.13 ± 9.98j 0.0132	**+0.18** ± **9.7j** **-0.0183**
UPFC only	-2.22 ± 3.4j 0.47	-1.08 ± 4.49j 0.234	-1.0 ± 5.36j 0.177
UPFC with damping controller	-3.1 ± 2.524j 0.47	-1.51 ± 4.42j 0.3229	-1.37 ± 5.27j 0.252

The superiority of the proposed controllers can be shown in Fig. 4. This Figure shows the change and angle at light loading condition due to 5% change in reference voltage. The effectiveness of the proposed controllers in damping low frequency oscillations is validated. Moreover, both UPFC and UPFC with auxiliary controller give better damping performance when the system is perturbed.

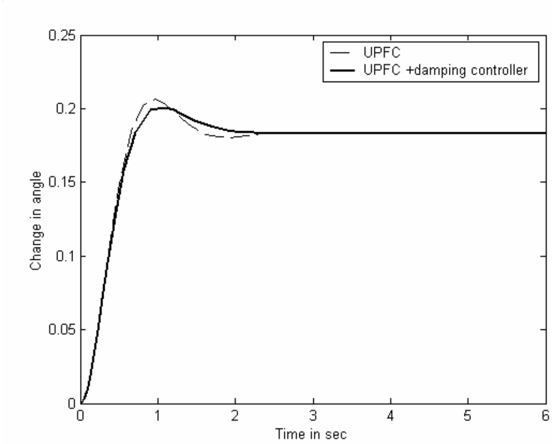

Fig. 4 Change in angle for light load.

Figs. 5-6 show the change of speed, and terminal voltage at normal loading condition with fixing the controllers parameters. From these Figures, it can be seen that the response with the proposed controller embedded with the supplementary damping controller provides good damping characteristics to low frequency oscillations and stabilizes the system faster compared to the case where UPFC without damping controller is acting. Also, It is clear that the voltage profile is greatly improved with the proposed controllers.

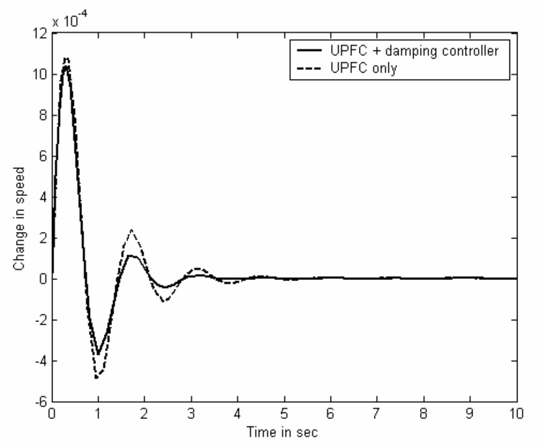

Fig. 5 Change in speed for normal load

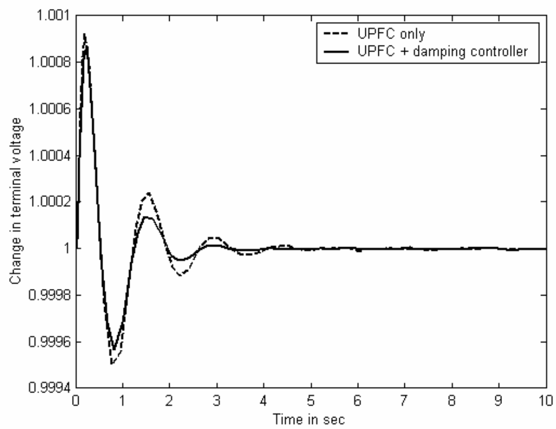

Fig. 6 Change in terminal voltage for normal load.

Fig. 7 shows the change of speed for heavy load condition. This Figure indicates the effectiveness of adding supplementary damping controller to the UPFC in damping the oscillations. Moreover, the settling time of the oscillations is approximately three second so the designed controller is capable of providing sufficient damping to the system oscillatory modes.

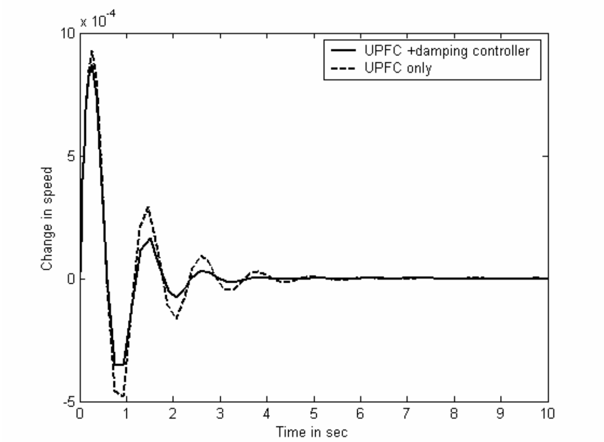

Fig. 7 Change in speed for heavy load condition.

A parameter variation test is also applied to assess the robustness of the proposed UPFC superimposed an auxiliary damping controller. Figs. 8-9 show the response of speed with variation in X_q and transmission line impedance. It is clear that, the system is stable with the proposed UPFC.

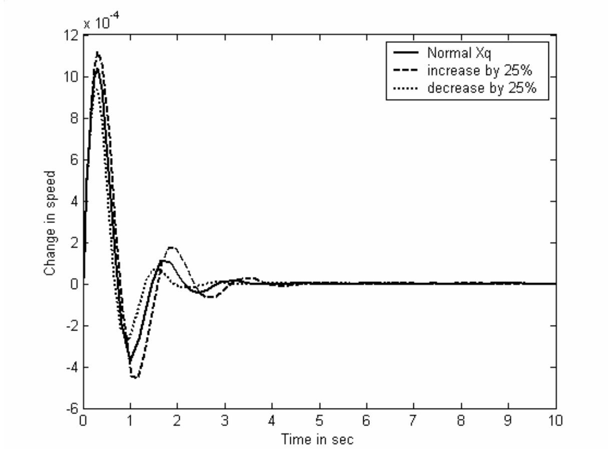

Fig. 8 Effect of X_q on speed response at normal load.

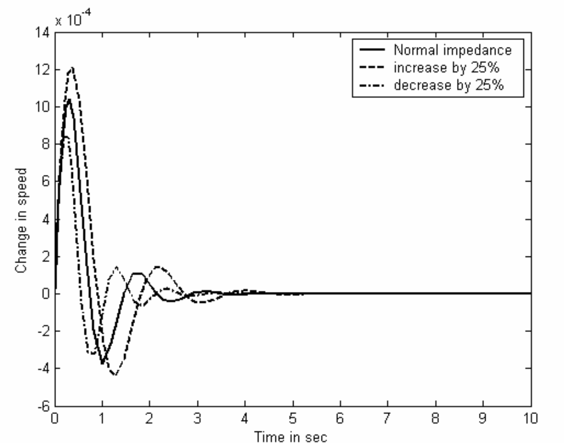

Fig. 9 Effect of changing line impedance in speed response.

The superiority of the proposed controller can be shown in Fig. 10 for a severe disturbance. A three phase fault is applied at infinite bus at t=1 sec and cleared after 5 cycles. The original system is restored upon the fault clearance. It is clear that, the proposed controller significantly provides good damping characteristics.

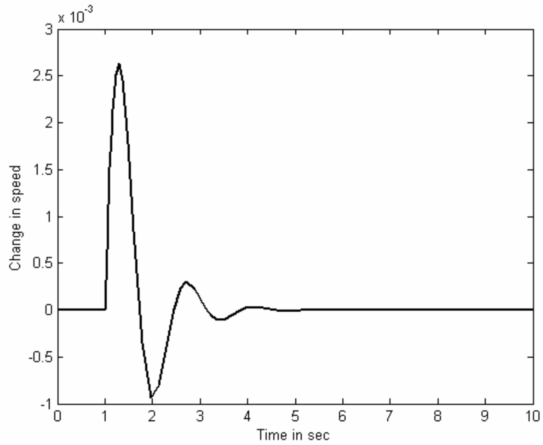

Fig. 10. Change in speed for three-phase fault at normal load.

7. Conclusions

BFOA is proposed in this paper to tune the parameters of UPFC. Moreover, an auxiliary damping controller is superimposed on UPFC to enhance the suppression of the power system oscillations. It was found that the optimized gains by Bacteria Foraging based UPFC with supplementary damping controller shows better performance than only UPFC. Also, it is seen that even when the generator is at different operating conditions other than the ones for which the controller parameters are optimized, the controller could damp out the oscillations efficiently. Simultaneous tuning of the UPFC controller parameters with the BFOA gives robust damping performance over wide range of operating conditions and parameter variations.

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Appendix

The system data are as shown below:

a) *Synchronous generator (p.u)*

x_d=1.07, X_q=0.6, x'_d=0.245, τ'_{do}=5.9, H=4.

b) *Excitation system:* K_A=400 T_A=0.05 sec.

c) *Transmission Line*: x_{tE} =0.1; x_{BV} =0.4

d) *Normal operating condition (p.u):* P=0.8; Q =0.15; Vt =1.

e) *DC link parameter*: C_{dc} =3 p.u ; V_{dc} =2 p.u.

f) *UPFC parameter:* x_E =0.1; x_B =0.1.

g) *Bacteria parameters:* Number of bacteria =10; number of chemotatic steps =10; number of elimination and dispersal events = 2; number of repoduction steps = 4; probability of elimination and dispersal = 0.25.