

## A Meta-heuristic Technique Based on Robust Power System Stabilizer

Vahid Sattarpour, Hodayoun Ebrahimian

Department of Electrical Engineering, Ardabil Branch, Islamic Azad University, Ardabil, Iran  
e-mail: vahidsattarpour@gmail.com

### Abstract

In this paper a robust Power System Stabilizer (PSS) is proposed based on inverse additive perturbation in a power system with wind farms. The proposed controller designed by new Improve Bacteria Foraging Algorithm (IBFA) to achieve robustness of this strategy where the optimization process is formulated based on an enhancement of system robust stability margin. The designed optimal PSS is based on Fuzzy Logic Controller (FLC). The effectiveness of the proposed technique is tested over ten machine 39 buses New England power system. Obtained results demonstrate the superiority of proposed technique over conventional PSS.

**Keywords:** BFA, Fuzzy controller, PSS, Multi-machine

### 1. Introduction

Some of the earliest power system stability problems included spontaneous power system oscillations at low frequencies. These Low Frequency Oscillations (LFOs) are related to the small signal stability of a power system and are detrimental to the goals of maximum power transfer and power system security. Once the adjustment of using damper windings on the generator rotors and turbines to control these oscillations was found to be satisfactory, the stability problem was thereby disregarded for some time [1]. But, as power systems began to be operated closer to their consistency limits, the weakness of a synchronizing torque among the generators was distinguished as a major cause of system instability [2]. Automatic Voltage Regulators (AVRs) helped to improve the steady-state stability of the power systems, but transient stability started a concern for the power system operators. With the development of large, interconnected power systems, another concern was the transfer of large amounts of power across extremely long transmission lines. The addition of a supplementary controller into the control loop, such as the introduction of Power System Stabilizers (PSSs) to the AVRs on the generators, supplies the means to reduce the inhibiting effects of low frequency oscillations [3]. Most of the time the PSSs and AVRs are locally controlled; which means that, the controller is designed to act on measurements such as bus voltage, generator shaft speed, or rotor angle of the associated machine's controls as presented in Figure 1.

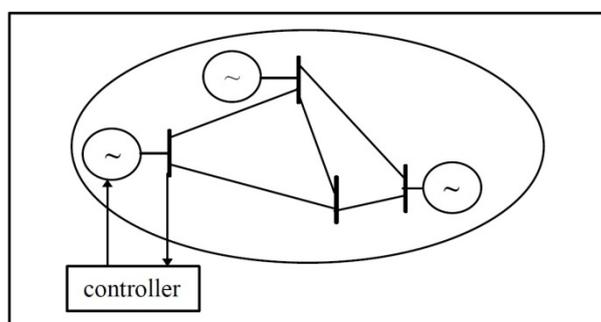


Figure 1. Local Feedback Controller

In the recent years, renewable electrical energy such as wind power generations, have achieved a significant level of penetration in the power systems due to infinite availability and low impact to environment. However, wind power generation is staggering in nature. Matching the supply and the demand is often a problem. The power output fluctuations from wind power generations cause a problem of low frequency oscillation, deteriorate the system stability and make the power system operation more difficult. The power frequency and the tie-line power deviations persist for a long term. In this status, the governor system may no longer be capable to absorb the frequency fluctuations due to its slow response [4].

Actually, several plants prefer to employ conventional lead-lag structure PSSs, due to the ease of online tuning and reliability [5]. However, the revenue of these controllers doesn't have good behavior in different load conditions. For this reason, a lot of intelligent algorithms have been introduced to optimal tuning of the PSSs parameters such as Ant Colony (AC) [6], Genetic Algorithm (GA) [7], Particle Swarm Optimization [8], Artificial Bee Colony [9] and etc.

The proposed algorithms are strong in optimization procedure but, they have some advantages and disadvantages. For instance, GA is a powerful optimization technique, independent on the complexity of problems where no prior knowledge is available. Also GA is very sufficient in finding global or near global optimal solution of the problem, it requires a very long run time that may be several minutes or even several hours depending on the size of the system under study [10-11].

To tackle of the mentioned backwards, in this paper a new Improve Bacteria Foraging Algorithm (IBFA) is presented based on fuzzy controller. The inverse additive perturbation is applied to represent unstructured system uncertainties. For tuning the optimal rule base of fuzzy controller, the concept of enhancement of system robust stability margin is formulated as the optimization problem. Also, the proposed IBFA is considered as a solution technique to problem. The obtained simulation results over ten machine-39 bus New England power system demonstrate the robustness of the proposed strategy.

The remaining parts of the paper are organized as follows. In the second section, the formulation of power system modeling is presented. The proposed controller structure is introduced in section three. The proposed IBFA and its application for the solution of the low oscillation problem with wind are presented in section four. Obtained numerical results from New England power system are presented in section five and compared with the other recently published methods. Section six concludes the paper.

## 2. Problem Statement

In this paper a multi-machine power system is considered as a test case where the third order model is presented in [12]. Actually, the proposed power system consists of ten generators and the electrical and mechanical part of ith generator is modeled as follow:

$$\begin{aligned}\dot{\delta}_i(t) &= w_i(t) - w_0 \\ \dot{w}_i(t) &= \frac{w_0}{M_i}(P_{mi} - P_{ei}(t)) - \frac{D_i}{M_i}(w_i(t) - w_0) \\ \dot{E}_{qi}(t) &= \frac{1}{T_{doi}}(E_{fi}(t) - E_{qi}(t)) \\ E_{qi}(t) &= E'_{qi}(t) + (x_{di} - x'_{di}) \cdot I_{di}(t) \\ V_{ti}(t) &= \frac{1}{x_{dsi}} [x_{si}^2 E_{qi}^2 + V_{si}^2 x_{qi}^2 + 2x_{si} x_{di} x_{dsi} P_{ei} \cot \delta_i]^{1/2} \\ P_{ei}(t) &= \sum_{j=1}^n E'_{qi}(t) E'_{qj}(t) (B_{ij} \sin(\delta_{ij}(t)) + G_{ij} \cos(\delta_{ij}(t))) \\ Q_{ei}(t) &= \sum_{j=1}^n E'_{qi}(t) E'_{qj}(t) (G_{ij} \sin(\delta_{ij}(t)) + B_{ij} \cos(\delta_{ij}(t))) \\ I_{di}(t) &= \sum_{j=1}^n E'_{qj}(t) (G_{ij} \sin(\delta_{ij}(t)) - B_{ij} \cos(\delta_{ij}(t))) = \frac{Q_{ei}(t)}{E'_{qi}(t)}\end{aligned}$$

$$I_{qi}(t) = \sum_{j=1}^n E_{qj}'(t) (B_{ij} \sin(\delta_{ij}(t)) - G_{ij} \cos(\delta_{ij}(t))) = \frac{P_{ei}(t)}{E_{qi}'(t)}$$

$$E_{qi}(t) = x_{adi} I_{fi}(t)$$

Also, it can be presented after mathematical transformers where,  $\Delta P_e$ ,  $\Delta w$  and  $\Delta V_t$  are quantities;

$$\begin{bmatrix} \Delta \dot{P}_{ei} \\ \Delta \dot{w}_i \\ \Delta \dot{V}_{ti} \end{bmatrix} = \begin{bmatrix} \frac{S_{Ei} - S_{Vi}}{T_{di}' S_{Vi}} & S_{Ei}' & -\frac{R_{Vi}' S_{Ei}}{T_{di}' S_{Vi}} \\ -\frac{w_{0i}}{H_i} & -\frac{D_i}{H_i} & 0 \\ \frac{S_{Ei} - S_{Vi}}{T_{di}' R_{Vi}' S_{Vi}} & \frac{S_{Ei}' - S_{Vi}'}{R_{Vi}'} & -\frac{S_{Ei}'}{T_{di}' S_{Vi}'} \end{bmatrix} \begin{bmatrix} \Delta P_{ei} \\ \Delta w_i \\ \Delta V_{ti} \end{bmatrix} + \begin{bmatrix} \frac{R_{Ei}'}{T_{d0i}'} \\ 0 \\ \frac{R_{Ei}'}{T_{d0i}' R_{Vi}'} \end{bmatrix} \Delta E_{fdi}$$

Where,

$\Delta P_{ei}$  is the state deviation in generator electromagnetic power for the  $i$ th subsystem

$\Delta w_i$  is the state deviation in rotor angular velocity for the  $i$ th subsystem,

$\Delta V_{ti}$  is the state deviation in the terminal voltage of the generator for the  $i$ th subsystem

$$S_{Ei} = \frac{E_{qi}' U_{si}}{X_{d\Sigma i}} \cos \delta_i + U_{si}^2 \frac{X_{d\Sigma i} - X_{q\Sigma i}}{X_{d\Sigma i} X_{q\Sigma i}} \cos 2\delta_i$$

$$S_{Ei}' = \frac{E_{qi}' U_{si}}{X_{d\Sigma i}'} \cos \delta_i + U_{si}^2 \frac{X_{d\Sigma i}' - X_{q\Sigma i}'}{X_{d\Sigma i}' X_{q\Sigma i}'} \cos 2\delta_i$$

$$R_{Ei} = \frac{U_{si}}{X_{d\Sigma i}} \sin \delta_i$$

$$R_{Ei}' = \frac{U_{si}}{X_{d\Sigma i}'} \sin \delta_i$$

$$S_{Vi} = S_{Ei} - R_{Vi} \frac{\partial U_{ti}}{\partial \delta_i}, R_{Vi} = S_{Ei} / \frac{\partial V_{ti}}{\partial E_{qi}'}$$

### A. Mechanical Oscillation Frequency

The linearized rotor motion equation for synchronous generator can be described as:

$$T_J \frac{d\Delta w}{dt} = \Delta T_m - \Delta T_e - \Delta T_D$$

Where,

$\Delta T_m$  is the mechanical input torque

$\Delta T_e$  is the electromagnetic torque and  $\Delta T_e = K_1 \Delta \delta + K_2 \Delta \delta$ ,

By neglecting the  $K_2 \Delta E'_{qi}$  the formulation can be described as;  $\Delta T_e = K_1 \Delta \delta + \Delta T_D$

$D$  is the natural damping constant

Accordingly the above equation after Laplace transformer and  $\Delta w = s \Delta \delta / w_0$  can be described as;

$$T_J \frac{s^2 \Delta \delta}{w_0} = -K_1 \Delta \delta - D \frac{s \Delta \delta}{w_0}$$

Which can be described as;

$$T_J s^2 + Ds + w_0 K_1 = 0$$

OR

$$s^2 + 2\zeta_n w_n s + w_n^2 = 0$$

Accordingly, we can achieve the following equation from above equations;

$$\zeta_n = D / 2\sqrt{w_0 T_J K_1}$$

$$w_n = \sqrt{w_0 K_1 / T_J}$$

Where,

$\zeta_n$  is the damping factor

$w_n$  is the undamped mechanical oscillation frequency

Usually the value of D is small, so the system damping is low. In order to enhance the system damping for suppressing the low frequency oscillation, the positive damping term is added by PSS.

### B. Power System Model

A 10-machine 39-bus power system with wind farms is considered as a test case for this paper which is presented in Figure 2. To assess the effectiveness and robustness of the proposed method over a wide range of loading conditions, different operation conditions are considered. Details of the system data and operating condition are given in Ref. [13]. The proposed power system is divided to four area with connected wind farm as shown in Figure 2.

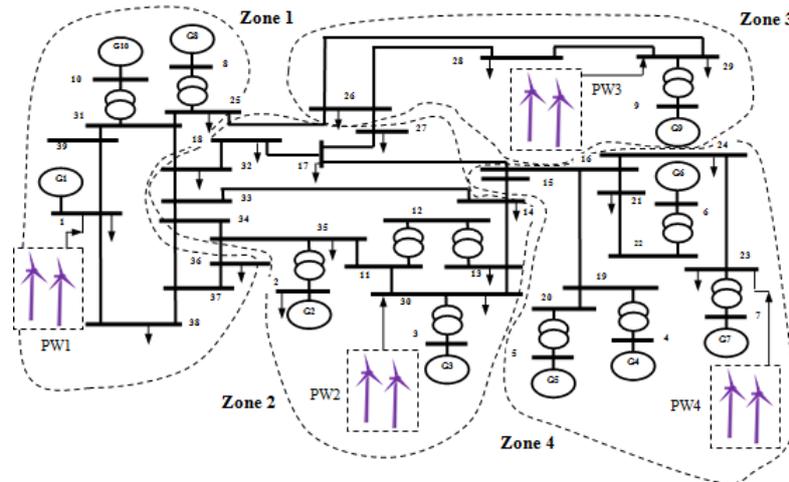


Figure 2. Structure of power system with wind farms

### C. Wind Power Model

It is clear that the output power of wind generator depends on wind velocity. The wind speed model chosen in this study consists of four-component model [14], that is defined as;

$$V_w = V_{WB} + V_{WG} + V_{WR} + V_{WN}$$

Where

WB V = Base wind velocity

WG V = Gust wind component

WR V = Ramp wind component

WN V = Noise wind component

The base wind velocity component is represented in literature as:

$$V_{WB} = K_B$$

Where KB is a constant and assumed to presenting the wind power. The gust wind velocity can be defined as;

$$V_{WG} = \begin{cases} 0 & t < T_{1G} \\ V_{\cos} & T_{1G} < t < T_{1G} + T_G \\ 0 & t > T_{1G} + T_G \end{cases}$$

Where,

$$V_{\cos} = (MAXG / 2) \{1 - \cos 2\pi [(t / T_G) - (T_{1G} / T_G)]\}$$

MAXG is the gust peak

TG is the gust period

T1G is the gust starting time

(1-cosine) gust is an essential component of wind velocity for dynamic studies

The ramp wind velocity component is described as:

$$V_{WG} = \begin{cases} 0 & t < T_{1R} \\ V_{ramp} & T_{1R} < t < T_{2R} \\ 0 & t > T_{2R} \end{cases}$$

Where,

$$V_{ramp} = MAXR[1 - (t - T_{2G}) / (T_{1R} - T_{2R})]$$

MAXR is the ramp peak

T1R is the ramp start time

T2R is the ramp maximum time

This component may be used to approximate a step change with  $T_{2R} > T_{1R}$ . Also, the random noise component can be described as:

$$V_{WN} = 2 \sum_{i=1}^N [S_V(\omega_i) \Delta \omega]^{1/2} \cos(\omega_i t + \phi_i) t < 0$$

Where,

$$\omega_i = (i - 1 / 2) \Delta \omega$$

$\phi_i$  is a random variable with uniform probability density on the interval 0 to  $2\pi$  and the spectral density function can be defined as:

$$S_V(\omega_i) = \frac{2K_N F^2[\omega_i]}{\pi^2 [1 + (F_{\omega_i} / \mu\pi)^2]^{4/3}}$$

Where  $K_N$  is the surface drag coefficient which is considered 0.004 and  $F$  is turbulence scale which is considered 2000, and  $\mu$  is the mean speed of wind at reference height. Various study have shown that values of  $N=50$ , and  $\Delta\omega = 0.5-2.0$  rad/s provide results of excellent accuracy.

D. Characteristic of wind generator output power

The output power of studied wind generator is expressed by a nonlinear function of the power coefficient  $C_p$  as function of blade pitch angle,  $\beta$ , and tip speed ratio,  $\lambda$ . The tip speed ratio is presented as follow:

$$\lambda = \frac{R_{blade} \omega_{Blade}}{V_w}$$

The power coefficient can be presented as:

$$C_p = (0.44 - 0.0167\beta) \sin\left[\frac{\pi(\lambda - 3)}{15 - 0.3\beta}\right] - 0.0184(\lambda - 3)\beta$$

At the end, the output of mechanical power for wind generator is:

$$P_w = \frac{1}{2} \rho A_r C_p V_w^3$$

Where,  $\rho$  ( $=1.25$  kg/m<sup>3</sup>) is the air density and  $A_r$  ( $=1735$  m<sup>2</sup>) is the swept area of blade.

### 3. Fuzzy Logic Controller

In classical control, the value of control is determined in relation to a number of data inputs using a set of equations to express the entire control process. Expressing human experience in the form of a mathematical formula is a very difficult task, if not an impossible one. Accordingly, Fuzzy Logic Controller (FLC) provides a simple tool to interpret this experience into reality [15]. FLCs are rule-based controllers with resembles structure with a knowledge based controller except that the FLC utilizes the principles of the fuzzy set theory in its data representation and its logic. The classic structure of FLC can be simply presented in Figure 3.

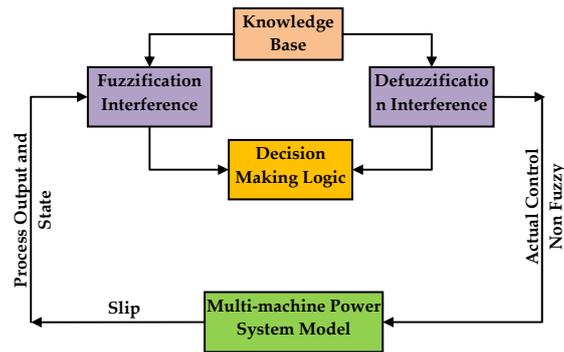


Figure 3. The conventional fuzzy controller structure

A set of fuzzy rules represents the FLC mechanism for adjusting the effect of certain system stimuli. Thus, the aim of fuzzy control systems is to replace a skilled human operator with a fuzzy rules-based system. The FLC also provides an algorithm which can convert the linguistic control strategy, based on expert knowledge, to automatic control strategies.

Thus, to reduce fuzzy system effort cost, in this paper proposed an intelligent technique for optimal tuning of fuzzy controller. Figure 4, shows the structure of the proposed IBFA-FPSS to improve power system stability.

#### 4. The IBFA Technique

In this part, the proposed improved Bacteria Foraging Algorithm (IBFA) is presented for the solution of the power system oscillation with wind farm effects. The BFA is an efficient population based stochastic search technique recently developed by Passino [16] which has found an increasing interest in the recent years as an optimization technique due to its high ability to search the promising areas of the solution space. The concept of this technique is based on the foraging mechanism of *E. coli* bacteria that are present in human intestines. The classic BFA technique is briefly illustrated in the flowchart of Figure 1 and can be described as the following step by step:

Step 1) The classic BFA consist of three main loop as; chemotaxis, reproduction and elimination-dispersal. To generate the initial population, i.e.  $\{DV(i,0,0,0)\}_{i=1, \dots, NS}$ , the NP decision variables of each bacterium are randomly generated within their allowable ranges.

$$\{DV(i, j, k, l)\}_{i=1, \dots, NS} = \{DV(1, j, k, l), DV(2, j, k, l), \dots, DV(NS, j, k, l)\}$$

Step 2) Set the counter of bacteria, denoted by  $i$ , to one ( $i=1$ ) to implement the chemotaxis loop.

Step 3) For bacterium  $i$ , the cost function of BF, denoted by  $CF(i, j, k, l)$ , is computed as follows:

$$CF(i, j, k, l) = AOF(i, j, k, l) + JCC(i, j, k, l)$$

Where  $AOF(i, j, k, l)$  represents augmented objective function of the proposed problem including its objective function The constructed AOF should be minimized. Where,  $JCC(i, j, k, l)$  is defined as follows:

$$J_{cc}(i, j, k, l) = \sum_{n=1}^{NS} J_{cc}^{i,n}(DV(i, j, k, l), DV(n, j, k, l))$$

where

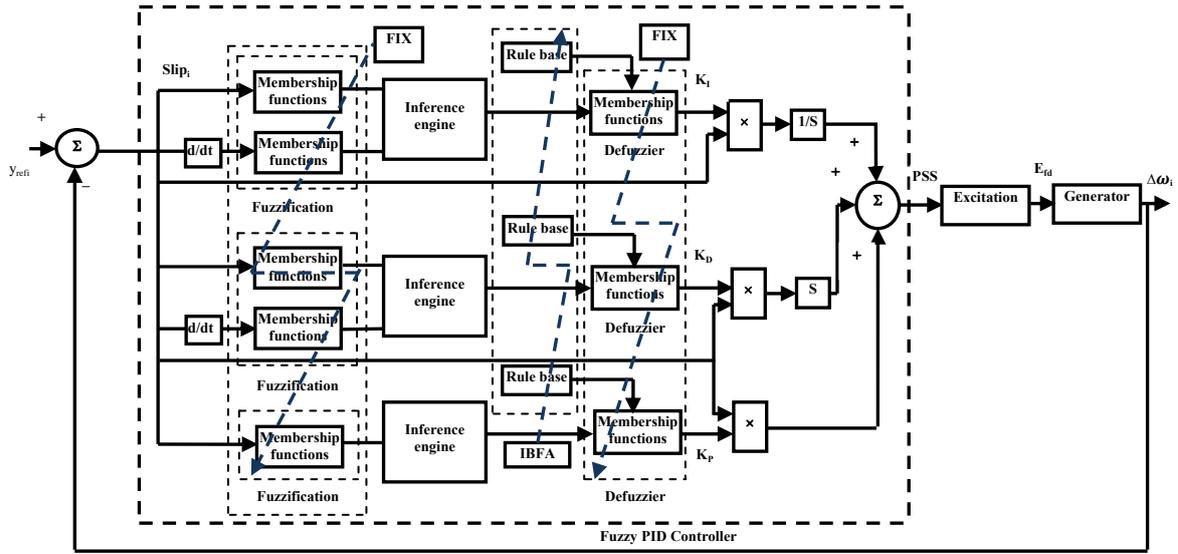


Figure 4. Proposed Fuzzy Controller Structure

$$J_{cc}^{i,n} (DV(i,j,k,l), DV(n,j,k,l)) = -d_{attract} \exp(-\omega_{attract} \cdot \|DV(i,j,k,l) - DV(n,j,k,l)\|^2) + h_{repellent} \exp(-\omega_{repellent} \cdot \|DV(i,j,k,l) - DV(n,j,k,l)\|^2)$$

In the above,  $\|.\|$  denotes the Euclidean norm. In other words, the additional cost function  $J_{cc}^{i,n} (DV(i,j,k,l), DV(n,j,k,l))$  for bacterium  $i$  is composed of NS terms measuring attracting and repelling effects between two bacteria  $i$  and  $n$ , respectively. In [16], the parameters of  $d_{attract}$ ,  $\omega_{attract}$ ,  $h_{repellent}$  and  $\omega_{repellent}$  are set as follows:  $\omega_{attract}=0.2$ ,  $\omega_{repellent}=10$ ,  $d_{attract}=h_{repellent}$

Step 4) The position of bacterium  $i$  is updated (or equivalently bacterium  $i$  moves), known as tumble, as follows:

$$DV(i,j+1,k,l) = DV(i,j,k,l) + C(i) \cdot \frac{\Delta(i,j,k,l)}{\|\Delta(i,j,k,l)\|}$$

This results in a step of size  $C(i)$  in the direction of the tumble (i.e.,  $\frac{\Delta(i,j,k,l)}{\|\Delta(i,j,k,l)\|}$ ) for bacterium  $i$ .

Step 5) The objective function of bacterium  $i$  for the next iteration of the chemotaxis loop ( $j+1$ ) is computed as:

$$CF(i,j+1,k,l) = AOF(i,j+1,k,l) + JCC(i,j+1,k,l)$$

Step 6) This step which is named as swim an inner counter  $m$  is initialized to zero ( $m=0$ ) and a parameter  $J_{last}$  is set as  $J_{last} = CF(i,j,k,l)$ .

Step 7) If  $i < NS$ , go to step 8; otherwise go to step 9.

Step 8) Increment  $i$  ( $i=i+1$ ) and go back to step 3.

Step 9) Increment  $j$  ( $j=j+1$ ).

Step 10) If  $j < N_{ch}$ , go back to step 2. Otherwise, go to the next step.

Step 11) Set the counter of bacteria to one ( $i=1$ ) to implement the outer loop, i.e. reproduction.

Step 12) The counter of reproduction loop is incremented ( $k=k+1$ ).

Step 13) If  $k < N_{re}$ , go to step 14; Otherwise; go to step 15.

Step 14) Set  $j=0$  and go back to step 2.

Step 15) Set  $i=1$  to implement the outermost loop of BF.

Step 16) The counter of elimination-dispersal loop is incremented ( $l=l+1$ ).

Step 17) If  $l < N_{ed}$ , go to step 18; otherwise got to step 19.

Step 18) Set  $j=0$  and  $k=0$  and go back to step 2.

Step 19) The BF algorithm is terminated and the best bacterium of the population owning the lowest value of the objective function CF is returned as the final solution of the optimization problem.

In this paper, a new version of BFA is presented to enhance the exploration capability and diversity of the search process of classic BFA [17]. Accordingly, to avoid generating similar search directions and enhance the diversity of the search process, mutation operation is modified as follows:

$$DV(i, j+1, k, l) = DV(i, j, k, l) + \beta \cdot \sum_{i_1, i_2 \in NS} (DV(i_1, j, k, l) - DV(i_2, j, k, l))$$

In above, each pair of the individuals of the population is randomly selected as (i1, i2) and their difference is considered in the summation. In this way, the effect of all possible difference vectors by the number of [NS/2] (instead of a single difference vector) is considered to construct the search direction. It is noted that the randomly selected pairs (i1, i2) for each individual DV(i,j,k,l) are different from those of the other individuals. To further enhance the exploration capability of the IBFA,  $\beta$  is randomly generated for each bacterium along the IBFA iterations with a uniform distribution in the interval (0,  $\beta_{max}$ ] as;

$$DV(i, j+1, k, l) = DV(i, j, k, l) + \beta(i, j, k, l) \cdot \sum_{i_1, i_2 \in NS} (DV(i_1, j, k, l) - DV(i_2, j, k, l))$$

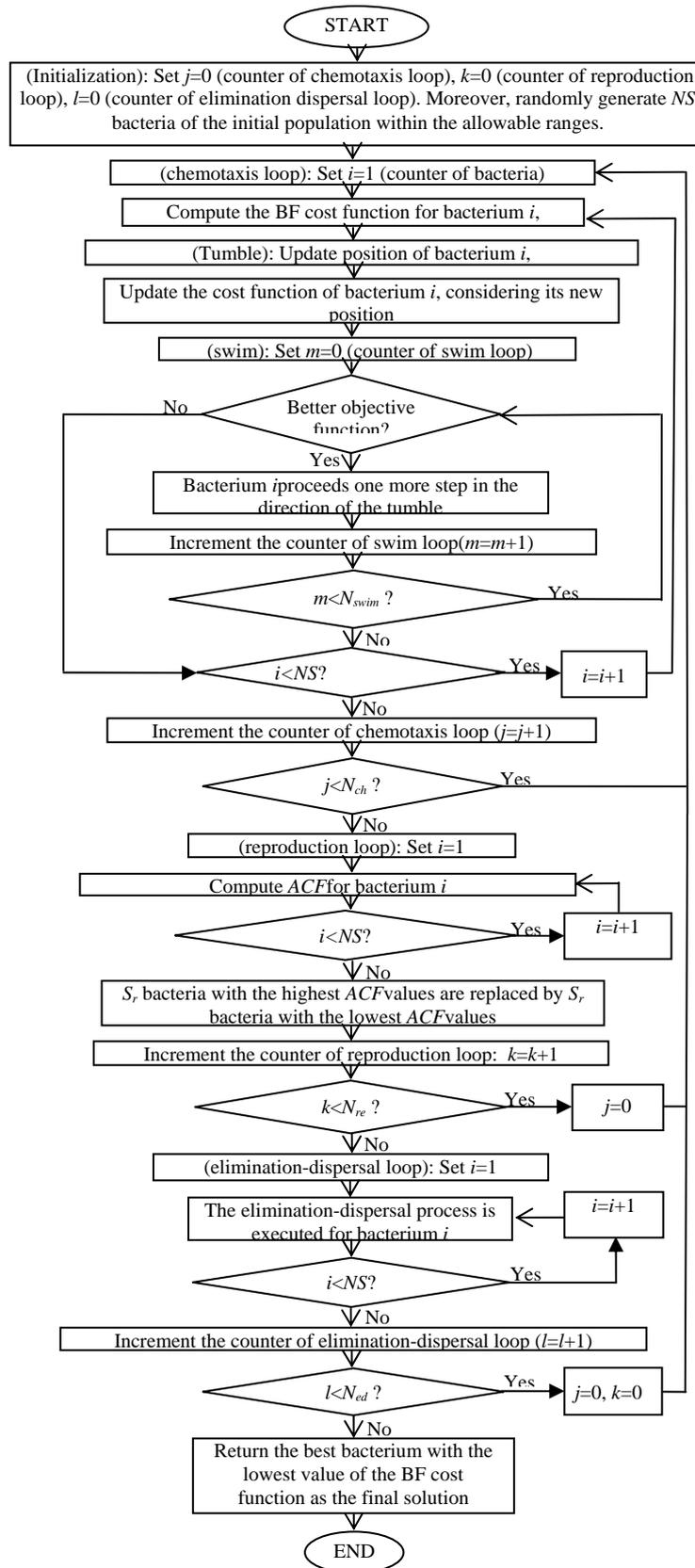


Figure 5. Flowchart of BFA

On the other hand, the proposed IBFA can benefit from both variable search directions and variable tumble steps (with high diversities) leading to higher search capability of the IBFA. Furthermore,  $\beta_{max}$  is adaptively changed along the iterations of the reproduction loop of the IBFA to enhance its convergence behavior:

$$\beta_{max}(k,l) = \frac{e^{(N_{re})} / (l \times N_{re})}{[(l \times N_{re}) + k + 1] \times 10}$$

Thus, the proposed IBFA begins with a high value of  $\beta_{max}(k,l)$  to search different regions of the solution space with high exploration. After a number of executions of the reproduction loop, when the bacteria enter the promising area,  $\beta_{max}(k,l)$  is adaptively reduced, limiting the range of variations of  $\beta(i,j,k,l)$ , to search the area with higher resolution.

**5. Simulation Results**

In this paper, an IBFA-FPSS is proposed, which combines the advantage of the IBFA and fuzzy control techniques to achieve good robust performance. It should be mentioned that obtaining the optimal decision-making logic for the proposed IBFA fuzzy control strategy is very important to achieve the desired level of robust performance [9], because it is a computationally expensive combinatorial optimization problem. Usually, the rule-base sets are determined by experience and control knowledge of a human expert. However, experts may not always be available and even when available it is a trial-and-error process that takes much time and cost [9]. The results of the fuzzy rule-base sets are listed in Tables 1-3. In the proposed rule-base optimization problem, the membership function sets for the  $K_{Pi}$ ,  $K_{Ii}$  and  $K_{Di}$  are defined as triangular partitions with five segments from 0 to 1 [18]. In this study the controllers are connected to G2 – G10 in the test system. Evaluation of the Integral of the Time multiplied Absolute value of the Error (ITAE) and Figure of Demerit (FD) based on the system performance characteristics are defined as [19]:

$$FD = (500 \times OS)^2 + (8000 \times US)^2 + 0.01 \times T_s^2 \quad ITAE = 100 \times \int_0^{t_{sim}} t(|\Delta\omega|)dt$$

Where, Overshoot (OS), Undershoot (US) and settling time of the rotor angle deviation of the machine is considered for evaluation of the FD. “Figure 5”, shows the plot of obtained fitness function value.

Table 1. Optimal Rule-Base for  $K_{Ii}$

	NB	NS	PS	PB
NB	NM	PB	ZO	PB
NS	NM	NB	ZO	ZO
Z	PM	NM	PM	PM
PS	NS	PM	NS	NM
PB	PM	NB	NS	NS

Table 2. Optimal Rule-Base for  $K_{Di}$

	NB	NS	PS	PB
NB	NS	NS	PB	NM
NS	PM	ZO	NB	ZO
Z	NM	NB	ZO	ZO
PS	NS	PM	PM	NB
PB	NM	NB	PM	NS

Table 3. Optimal Rule-Base for  $K_{Pi}$

	NB	NS	PS	PB
NB	NS	NS	PB	NM
NS	PM	ZO	NB	ZO
Z	NM	NB	ZO	ZO
PS	NS	PM	PM	NB
PB	NM	NB	PM	NS

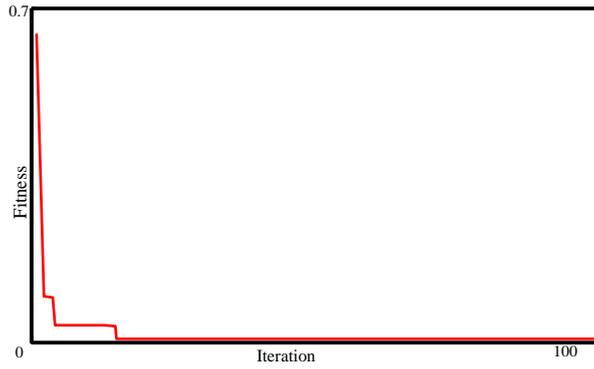


Figure 6. Variations of the fitness functions

The wind velocity in four area is presented in Figure 7. Also, wind power generations are presented in Figure 8, and Figure 9-11 shows tie-line power deviation in nominal load condition.

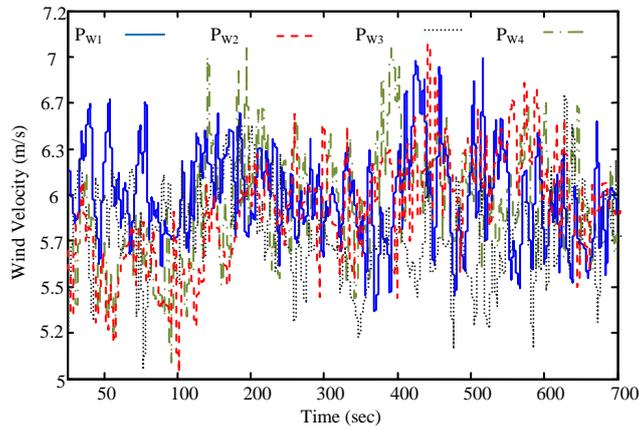


Figure 7. Wind velocity

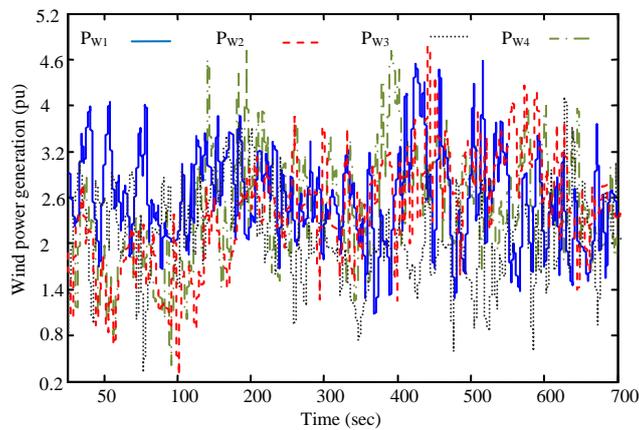


Figure 8. Wind power generations

- *Scenario 1*

In this paper two scenarios are presented to test the proposed control strategy in New England power system. For the first scenario, it is very important that, the performance of the proposed controller is tested under transient conditions by applying a 6-cycle three-phase fault or increasing the mechanical torque. So, in this scenario a 6-cycle three-phase fault is applied in line 26-29 and bus 29. The responses of generators 1, 3, 7 and 9 are presented in Figure 12. Also the numerical results of FD and ITAE are presented in Table 4.

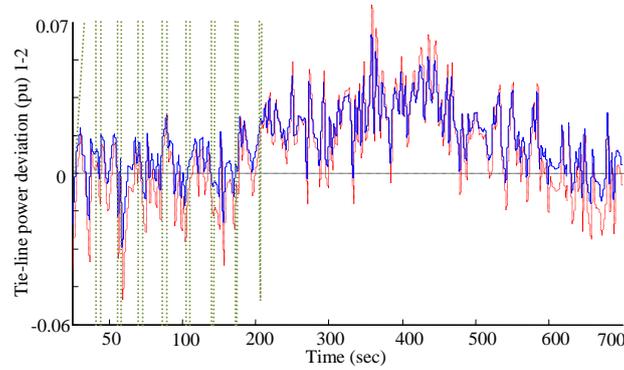


Figure 9. System response in first scenario under nominal load condition (Solid: Proposed, Dashed: CPSS, Doted: No-PSS)

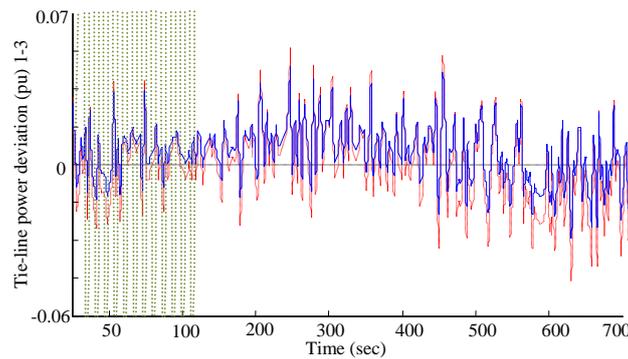


Figure 10. System response in first scenario under heavy load condition (Solid: Proposed, Dashed: CPSS, Doted: No-PSS)

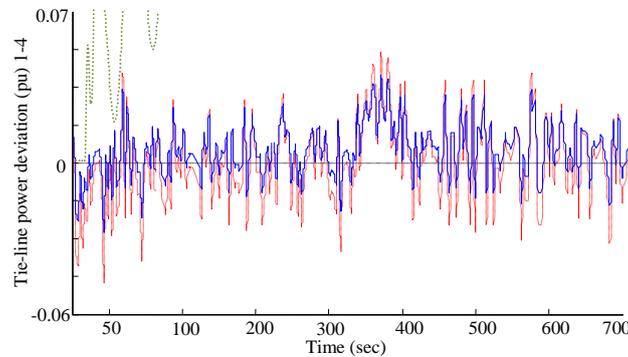


Figure 11. System response in first scenario under light load condition (Solid: Proposed, Dashed: CPSS, Doted: No-PSS)

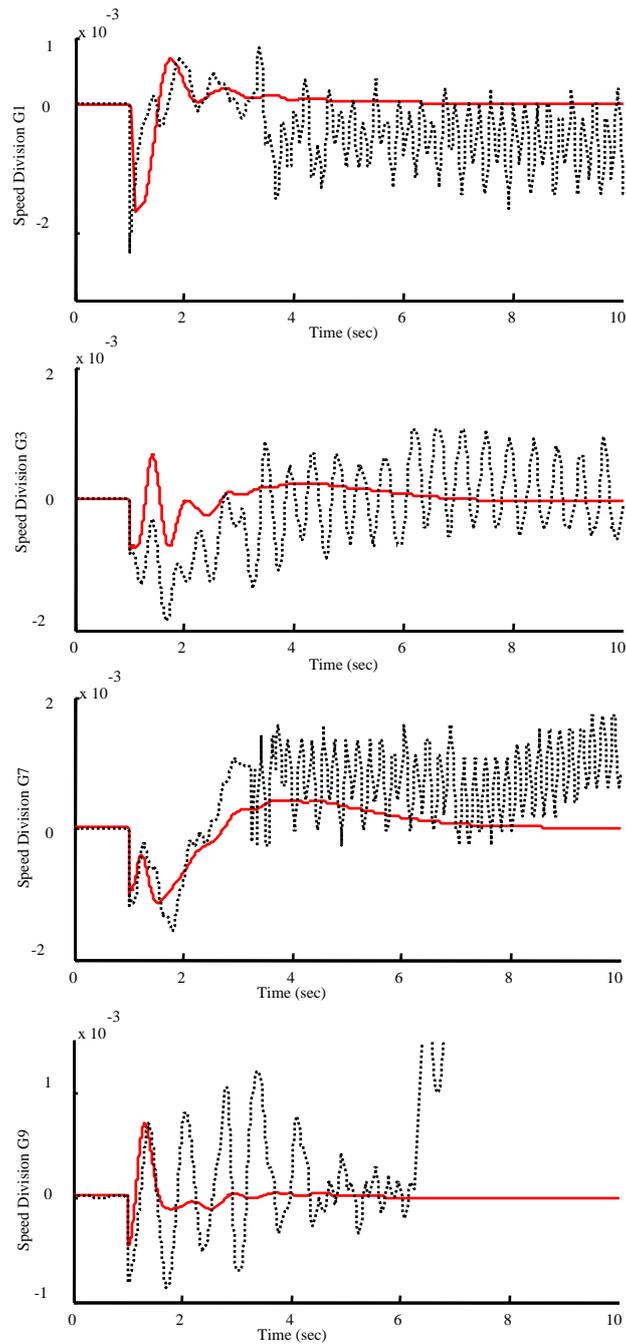


Figure 12. Generators response at first scenario under nominal load condition (Solid: Proposed, Dashed: CPSS)

- Scenario 2

In the second scenario a 0.1 step is applied over the torque of generators. The tie-line response of power system is presented in Figure 13-15. Also, the responses of 1, 3, 7 and 9 generators are presented in Figure 16. The numerical results of FD and ITAE are presented in Table 5.

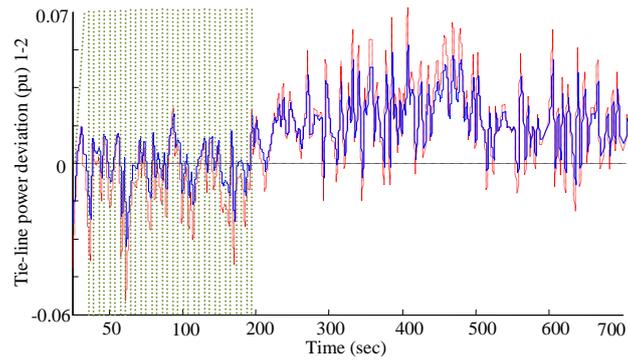


Figure 13. System response in second scenario under nominal load condition (Solid: Proposed, Dashed: CPSS, Dotted: No-PSS)

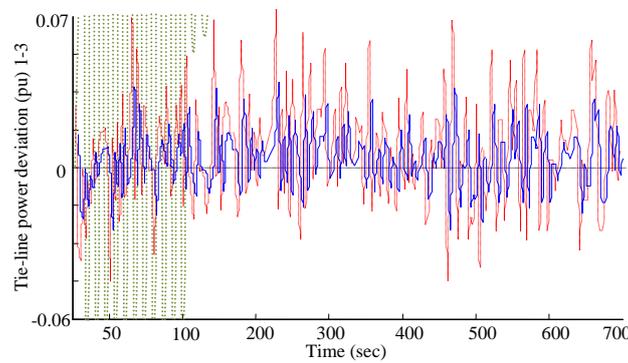


Figure 14. System response in second scenario under heavy load condition (Solid: Proposed, Dashed: CPSS, Dotted: No-PSS)

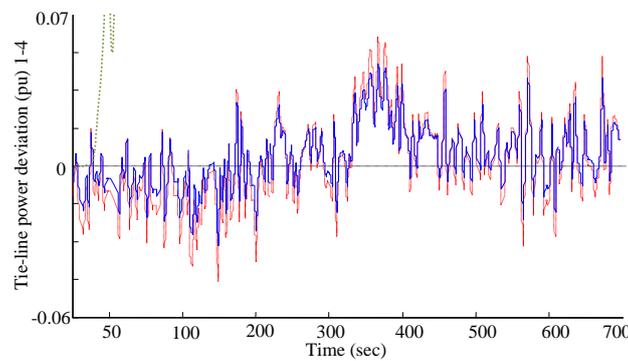


Figure 15. System response in second scenario under light load condition (Solid: Proposed, Dashed: CPSS, Dotted: No-PSS)

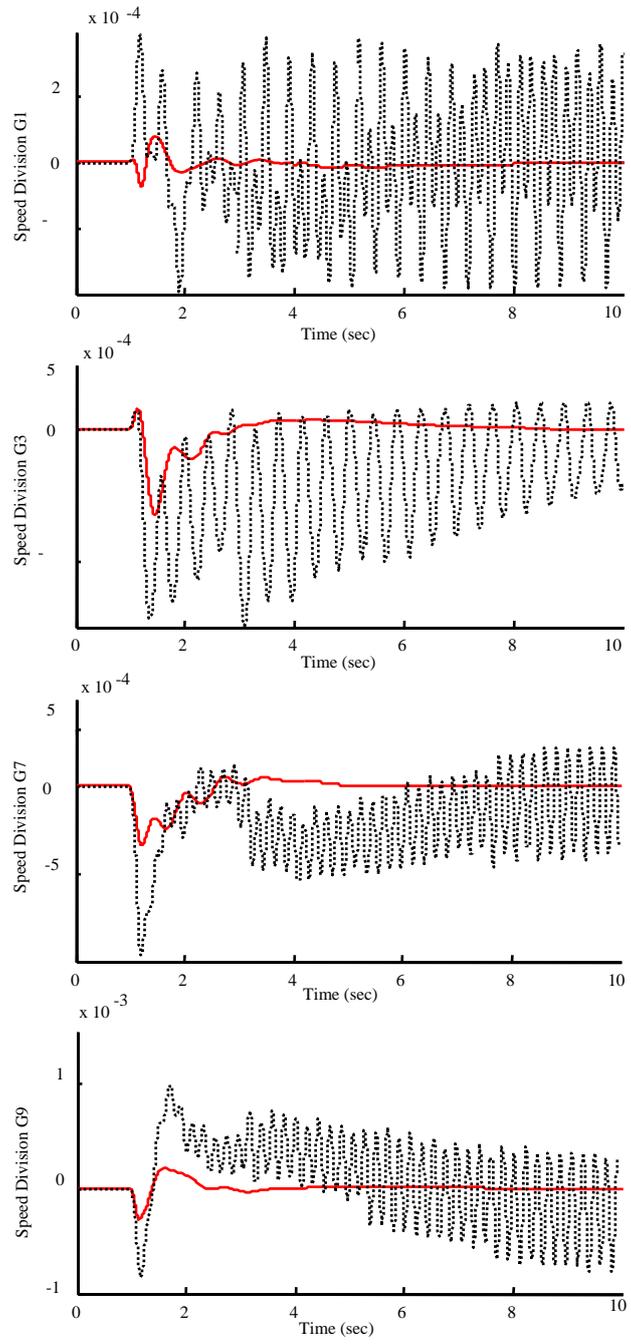


Figure 16. Generators response at first scenario under nominal load condition (Solid: Proposed, Dashed: CPSS)

Table 4. Calculate of FD and ITAE for different load changes.

Change load	IBFA		CPSS	
	ITAE	FD	ITAE	FD
25%	2.8293	1.6251	9.656	8.455
20%	1.1093	1.2543	8.856	8.490
15%	1.1110	1.0137	8.890	8.466
10%	1.0123	1.0225	8.265	8.349
5%	1.0313	1.0129	8.853	8.763
Nominal	1.0113	1.2421	8.876	8.223
-5%	1.2413	1.2663	8.243	8.324
-10%	1.1542	1.2514	8.866	8.365
-15%	1.1652	1.2665	8.234	8.387
-20%	1.1334	1.1322	8.734	8.376
-25%	2.1542	1.1652	9.029	8.376

Table 5. Calculate of FD and ITAE for different load changes.

Change load	IBFA		CPSS	
	ITAE	FD	ITAE	FD
25%	2.3411	1.0321	9.6947	8.3109
20%	1.0193	1.0302	8.4771	8.0382
15%	1.0232	1.0203	8.4571	8.6898
10%	1.0133	1.0243	8.4539	8.0117
5%	1.0322	1.0421	8.5404	8.0446
Nominal	1.0244	1.0321	8.5069	8.0488
-5%	1.1093	1.0445	8.5294	8.0551
-10%	1.1034	1.0421	8.4432	8.0621
-15%	1.1033	1.1342	8.5570	8.0726
-20%	1.1045	1.1034	8.7436	8.1157
-25%	1.1135	1.1211	12.6553	8.0117

## 6. Conclusion

In this paper, a design scheme of robust PSS ten-machine New England power system using by considering inverse additive perturbation in a power system with wind farms is presented through hybrid technique of fuzzy controller and improved BFA. By proposed IBFA, the rule based of fuzzy controller is optimized to damp power system oscillation where. The proposed technique is tested in various load condition for the solution of the low frequency oscillation problem in power system. The proposed test case is compared with Classic PSS through different load conditions and numerical results of ITAE and FD. Obtained numerical results and simulation results demonstrate that the proposed strategy satisfied the stability of multi-machine power system.

## References

- [1] G Shahgholian, A Rajabi, B Karimi. "Analysis and Design of PSS for Multi-Machine Power System Based on Sliding Mode Control Theory". *International Review of Electrical Engineering (I.R.E.E.)*. 2010; 5(5): 2241-2250.
- [2] Hagh MT and Ghadimi N. Multisignal histogram-based islanding detection using neuro-fuzzy algorithm. *Complexity*. 2014; doi: 10.1002/cplx.21556.
- [3] P Kundur. *Power system stability and control*. New York: McGraw- Hill. 1994.
- [4] Eskandari Nasab M, Maleksaeedi I, Mohammadi M and Ghadimi N. A new multiobjective allocator of capacitor banks and distributed generations using a new investigated differential evolution. *Complexity*. 2014; 19: 40–54. doi: 10.1002/cplx.21489.
- [5] MJ Basler, RC Schaefer. "Understanding Power System Stability". *IEEE Trans. Industry Applications*. 2008; 44: 463-474.
- [6] M Caner, N Umrkan, S Tokat, S Vakkas Ustun. "Determination of Optimal Hierarchical Fuzzy Controller Parameters According to Loading Condition with ANN". *Expert Systems with Applications*. 2008; 34: 2650-2655.
- [7] Morsali R, Mohammadi M, Maleksaeedi I and Ghadimi N. A new multiobjective procedure for solving nonconvex environmental/economic power dispatch. *Complexity*. 2014; 20: 47-62. doi: 10.1002/cplx.21505.
- [8] Ghadimi N. A new hybrid algorithm based on optimal fuzzy controller in multimachine power system. *Complexity*. 2014; doi: 10.1002/cplx.21544.

- [9] Abido M. A novel approach to conventional power system stabilizer design using tabu search. *Int. J. Elect. Power Energy Syst.* 1999; 21(6): 443-454.
- [10] Abdel-Magid YL, Abido MA. Optimal multiobjective design of robust power system stabilizers using genetic algorithms. *IEEE Trans. Power Syst.* 2003; 18(3): 1125-1132.
- [11] Eslami M, Shareef H, Mohamed A. Damping of Power System Oscillations Using Genetic Algorithm and Particle Swarm Optimization. *International Review of Electrical Engineering.* 2010; 6(5): 2745-2753.
- [12] Ghadim, N. An adaptive neuro-fuzzy inference system for islanding detection in wind turbine as distributed generation. *Complexity.* 2014; doi: 10.1002/cplx.21537
- [13] YL Abdel-Magid, MA Abido, S Al-Baiyat, AH Mantawy. "Simultaneous Stabilization of Multi-machine Power Systems Via Genetic Algorithms." *IEEE Trans. Power Syst.* 1999; 4(4): 1428-1439.
- [14] Dong-Jiang & Li Wang. Small-signal stability analysis of an autonomous hybrid renewable energy power generation/energy storage system part I: time-domain simulations. *IEEE Transactions on Energy Conversion.* 2008; 23(1): 311-320.
- [15] I Boldea and SA Nasar. *Electric Machine Dynamics.* Macmillan Publishing Company. 1986.
- [16] KM Passino. "Biomimicry of bacterial foraging for distributed optimization and control". *IEEE Control Syst. Mag.* 2002; 22(3): 52-67.
- [17] KY Lee, MA El-Sharkawi. *Modern Heuristic Optimization Techniques.* John Wiley & Sons Inc. 2008.
- [18] O Abedinia, Mohammad S Naderi, A Ghasemi. *Robust LFC in Deregulated Environment: Fuzzy PID using IBFA.* Proceeding of the IEEE International Power & Energy Society Power Systems Conference and Exposition, Italy, Rome (EEEIC), 2011: 74-77.
- [19] Ishra S, Tripathy M, Nanda J. Multi-machine power system stabilizer design by rule based bacteria foraging. *Electr. Power Syst. Res.* 2007; 77(12): 1595-1607.