A Novel Fuzzy Based Multi Objective Honey Bee Mating Optimization Algorithm for PSS Design in SMIB

H. A. Shayanfar*  
Center of Excellence for Power System Automation and Operation  
Iran University of Science and Technology, Tehran, Iran  
hashayanfar@gmail.com

H. Shayeghi  
Technical Eng. Department  
University of Mohaghegh Ardabili  
Ardabil, Iran  
lshayeghi@gmail.com

A. Ghasemi  
Technical Eng. Department  
Young Researcher Club, Islamic Azad University, Ardabil, Iran  
ghasemi.agm@gmail.com

Abstract- This paper presents a Novel Fuzzified Multi Objective (MO) version of Honey Bee Mating Optimization (MOHBMO) approach for optimal tuning of linear parameters (such as the gain and time constant) and nonsmooth nonlinear parameters (such as saturation limits) of Power System Stabilizer (PSS). The problem of robustly tuning of PSS based SMIB design is formulated as an optimization problem according to the time domain-based and eigenvalue based objective functions which are solved by the MOHBMO technique that has a strong ability to find the most optimistic results. The effectiveness of the proposed Fuzzy based MOHBMO based PSS is demonstrated on a Single-Machine Infinite-Bus (SMIB) power system through the nonlinear time domain simulation and some performance indices under different operating conditions in comparison with the SPEA algorithm based tuned stabilizer and conventional PSS.

Keywords: PSS Design, HBMO, MOHBMO, Low Frequency Oscillations, SMIB.

1. Introduction

Low frequency oscillations are detrimental to the goals of maximum power transfer and optimal power system security [1]. A contemporary solution to this problem is the addition of power system stabilizers to the automatic voltage regulators on the generators in the power system. The damping provided by this additional stabilizer provides the means to reduce the inhibiting effects of the oscillations [2]. The application of Power System Stabilizer (PSS) can help in damping out these oscillations and improve the system stability. The traditional and till date the most popular solution to this problem is application of the Conventional Power System Stabilizer (CPSS). However, continual changes in the operating condition and network parameters result in corresponding change in system dynamics. This constantly changing nature of power system makes the design of CPSS a difficult task [3].

A more reasonable design of the PSS is based on the gain scheduling and adaptive control theory as it takes into consideration the nonlinear and stochastic characteristics of the power systems [4-5]. This type of stabilizer can adjust its parameters on-line according to the operating condition. Many years of intensive studies have shown that the adaptive stabilizer can not only provide good damping over a wide operating range but more importantly, it can also solve the coordination problem among the stabilizers. Many random heuristic methods, such as like Improved honey bee mating optimization algorithm, chaotic optimization algorithm, artificial bee colony algorithm, Particle Swarm Optimization (PSO), Improved version of PSO algorithm have recently received much interest for achieving high efficiency and search global optimal solution in the problem space and they have been applied to the problem of PSS design [6-11]. These evolutionary based methods are heuristic population-based search procedures that incorporate random variation and selection operators. In addition, the PSS design problem was formulated as a single objective for optimization in all of the above methods.

It should be noted that the PSS design problem is a multiobjective optimization problem due to system characteristics and nonlinear behavior of the power systems. Thus, a fuzzy based Multi Objective Honey Bee Mating Optimization (MOHBMO) technique is proposed for optimal tune of PSS parameters to improve power system low frequency oscillations damping in this paper. The HBMO algorithm is a typical swarm-based approach to optimization, in which the search algorithm is inspired by the honey-bee mating process [12-13] and has emerged as a useful tool for engineering optimization. There is no absolute global best in MOHBMO, but rather a set of nondominated solutions. Also, there may be no single local best queen for each individual of the colony. Selecting the global best and local best to guide the colony bees becomes nontrivial task in multi-objective domain. Thus, for non-

*Corresponding Author (hashayanfar@gmail.com)
dominance solutions sorting the Pareto archive maintenance approach and to ensure proper diversity amongst the solutions of the non-dominated solutions in Pareto archive maintenance the crowding distance measure concept is used [14].

In this study, the problem of robust PSS design is formulated as a multi objective optimization problem and MOHBMO technique is used to solve it. Two performance indices based on time and frequency domains characteristics are defined and used to form the objective function of the design problem. The proposed MOHBMO based designed PSS has been applied and tested on a weakly connected power system under wide range of operating conditions to illustrate their ability to provide efficient damping of low frequency oscillations.

2. Power system model

For stability analysis of power system adequate mathematical models describing the system are needed. The models must be computationally efficient and be able to represent the essential dynamics of the power system. The stability analysis of the system is generally attempted using mathematical models involving a set of nonlinear differential equations. A schematic diagram for the test system is shown in Fig. 1. The generator is equipped with excitation system and a power system stabilizer. System data are given in Appendix.

The synchronous generator is represented by model 1.1, i.e. with field circuit and one equivalent damper winding on q axis. The nonlinear dynamic equations of the SMIB system considered can be summarized as [2, 11].

\[ \delta = \omega_p S_m \]
\[ \frac{dS_m}{dt} = \frac{1}{2H} (-DS_m + T_m - T_r) \]
\[ E_q^* = \frac{1}{T_{do}} (E_{qd} + (x_d - x'_d)j_d - E_q^*) \]
\[ E_{fd} = \frac{1}{T_d} (k_d (v_{ref} - v_i + V_q) - E_{fd}) \]
\[ T_e = E_{q'dq} + (x_d' - x'_d)j_{d'dq} \]

2.1. PSS model

The structure of PSS, to modulate the excitation voltage is shown in Fig. 2. The structure consists of a gain block with gain K, a signal washout block and two-stage phase compensation blocks. The input signal of the proposed method is the speed deviation (\(\Delta \omega\)) and the output is the stabilizing signal \(V_S\) which is added to the reference excitation system voltage. The signal washout block serves as a high-pass filter, with the time constant \(T_w\), high enough to allow signals associated with oscillations in input signal to pass unchanged. From the viewpoint of the washout function, the value of \(T_w\) is not critical and may be in the range of 1 to 20 seconds [11]. The phase compensation block (time constants \(T_1\), \(T_2\) and \(T_3\), \(T_4\) ) provides the appropriate phase-lead characteristics to compensate for the phase lag between input and the output signals.

3. Multi Objective HBMO

A. Brief HBMO Review

A honey-bee colony typically consists of a single egg laying long-lived queen, several thousand drones (depending on the season), workers and a large family of bees living in one bee-hive [12]. Each bee undertakes sequences of actions which unfold according to genetic, ecological and social condition of the colony.

A mating flight starts with a dance performed by the queen who then starts a mating flight during which the drones follow the queen and mate with her in the air. After the mating process, the drones die. In each mating, sperm reaches the spermatheca and accumulates there to form the genetic pool of the colony. Each time a queen lays fertilized eggs, she randomly retrieves a mixture of the sperm accumulated in the spermatheca to fertilize the egg and this task can only be done by the queen [16-17].

The HBMO algorithm combines different phases of the marriage process of the honey bee. It starts with random generation of a set of initial solutions. Based on their fitness, randomly generated solutions are then
ranked. The fittest solution is named queen, whereas the remaining solutions are categorized as drones (i.e., trial solutions). In order to form the hive and start mating process, the queen, drones and workers (predefined heuristic functions) should be defined. Each queen is characterized with a genotype, speed, energy and a spermatheca with defined capacity. In the next step, drones must be nominated to mate with the queen probabilistically during the mating flight. At the start of the flight, the queen is initialized with some energy content and returns to her nest when the energy is within some threshold of either near zero or when the spermatheca is full. The mating flight may be considered as a set of transitions in a state-space (the environment). An annealing function is used to describe the probability of a drone \((D)\) that successfully mates with the queen \((Q)\) as follows [12]:

\[
prob(Q,D) = e^{-\frac{\Delta(f)}{S(t)}}
\]

(3)

Where, \(\Delta(f)\) is the absolute difference of the fitness of \(D\) and the fitness of \(Q\) and the \(s(t)\) is the speed of queen at time \(t\). The fitness of the resulting chromosomes of drone, queen or brood is determined by evaluating the value of the objective function. After each transition in space, the queen’s speed and energy decays is given by:

\[
S(t+1) = \alpha \times S(t)
\]

(4)

\[
E(t+1) = E(t) - \gamma
\]

(5)

Where, \(\alpha(t)\) is speed reduction factor and \(\gamma\) is the amount of energy reduction after each transition \((\alpha, \gamma \in [0,1])\).

B. MOHBMO

In most of practical cases, multi-objective optimization problems require simultaneous optimization of several incommensurable and often competitive/conflicting objectives. Because of presence of the multiple conflicting objectives, there is not exist one solution, which is the optimum of all objectives simultaneously. Instead, the solutions exist in the form of alternative trade-offs, also known as the Pareto optimal solutions. In other word, a multi-objective optimization problems always has a set of optimal solutions, for which there is no way to improve one objective value without deterioration of at least one of the other objective values. Pareto dominance concept classifies solutions as dominated or non-dominated solutions and the “best solutions” are selected from the non-dominated solutions. To sort non-dominated solutions, the first front of the non-dominated solution is assigned the highest rank and the last one is assigned the lowest rank. When comparing solutions that belong to a same front, another parameter called crowding distance is calculated for each solution. The crowding distance is a measure of how close an individual is to its neighbors. Large average crowding distance will result in better diversity in the population [14]. In order to investigate multi-objective problems, some modifications in the HBMO algorithm were made.

Here, fuzzy set theory has been implemented to derive efficiently a candidate Pareto optimal solution for the decision makers [16]. The fuzzy set theory has been implemented to derive efficiently a solution from the set of non-dominated solutions. The fuzzy decision making function is represented by the membership function to replace each variable as a precise value. Fig. 3. depicts the membership function \(\mu_c\) for the fuzzy variable signifying total fuel cost \(f_c\). The decision maker is fully satisfied with the cost if, \(\mu_c\) is one, and not satisfied at all if \(\mu_c\) is zero. Therefore, the value of membership function indicates the adaptability of the economy index. Due to the imprecise nature of decision maker’s judgment, the \(i^{th}\) objective function of a solution in the non-dominated set \(f_i\) is represented by a membership function \(\mu_{i,k}\) defined as [17]:

\[
\mu_i = \frac{f_i^{max} - f_i}{f_i^{max} - f_i^{min}}
\]

(6)

Fig. 3. Membership function of fuzzy cost.

Where \(f_i^{max}\) and \(f_i^{min}\) are the maximum and minimum values of \(f_i\) objective, respectively. We can have:

\[
FDM_i = \begin{cases} 
0 & \mu_i \leq 0 \\
\mu_i & 0 < \mu_i < 1 \\
1 & \mu_i \geq 1 
\end{cases}
\]

(7)

For each non-dominated solution \(k\), the normalized membership function \(FDM^k\) can be defined as follows:

\[
FDM^k = \frac{\sum FDM_i^k}{\sum \sum FDM_i^k}
\]

(8)

The best compromise solution of PSS problem is the one having the maximum value of \(FDM^k\) as fuzzy decision making function. Where \(M\) is the total number of non-dominated solutions. Then all the solutions are arranged in descending order according to their membership function values which will guide the decision makers with a priority list of non-dominated solutions in view of the current operating conditions. Flowchart of MOHBMO algorithm is summarized in Fig. 4.
4. Problem formulation

In the present study, washout time constant $T_W = 10$ sec is used for the given lead-lag structure in Fig. 2. For the optimal tuning of the PSS parameters in Fig. 4, both linear parameters ($K$, $T_1$, $T_2$, $T_3$, and $T_4$) and nonlinear parameters ($V_{max}$ and $V_{min}$) are to be determined. It is worth mentioning that the PSS is designed to minimize the power system oscillations after a large disturbance so as to improve the power system stability. To increase the system damping to the electromechanical modes and find appropriate location of PSSs the objective functions for optimization is defined as follow:

$$J_1 = \sum_{j=1}^{Np} \int_{t_{sim}}^{t} \Delta \omega dt + 0.07 \times OS$$

$$J_2 = \sum_{j=1}^{Np} \sum_{i,j} \left( \sigma_i - \sigma_j \right)^2 + 5 \times \sum_{j=1}^{Np} \sum_{i,j} \left( \zeta_i - \zeta_j \right)^2$$

Where $\sigma_i$ and $\zeta_i$ are the real part and the damping ratio of the $i$th eigenvalue of the $j$th operating point. The $t_{sim}$ is the time range of simulation and $NP$ is the total number of operating points for which the optimization is carried out.

Cost function as given in Eqs. (9) and (10), which considers a multiple of operating conditions are given in Table 1. The operating conditions are considered for wide range of output power at different power factors.

Results of the PSS parameter set values based on the objective function $J_1$ (by applying a three phase-to-ground fault for 100 ms at generator terminal at $t = 1$ sec) and $J_2$, using the proposed MOHBMO and SPEA [15] and CPSS [2] algorithms are given in Table 2. Fig. 5 shows the minimum fitness functions evaluating process.

5. Simulation results

The behavior of the proposed MOHBMO based designed PSS (MOHBMO-PSS) under transient conditions is verified by applying disturbance and fault clearing sequence under different operating conditions. In comparison with the SPEA based tuned PSS (SPEARSS) and classical PSS. The disturbances are given at $t = 1$ sec. System responses in the form of slip
(\(S_a\)) are plotted. The following types of disturbances have been considered.

**Scenario 1:** A step change of 0.1 pu in input mechanical torque.

**Scenario 2:** A three phase-to-ground fault for 100 ms at generator terminal.

Figure 6 shows the system response at the lagging power factor operating conditions with weak transmission system for scenario 1. It can be seen that the system with CPSS is highly oscillatory. MOHBMO and SPEA based tuned stabilizers are able to damp the oscillations reasonably well and stabilize the system at all of the operating conditions. Figure 7 depicts the responses of same operating conditions but with strong transmission system. System is more stable in this case, following any disturbance. Both PSSs improve its dynamic stability considerably and MOHBMOPSS shows its superiority over SPEAPSS and CPSS. Figure 8 refers to a three-phase to ground fault at generator terminal. Figure 9 depicts the system response in scenario 1 with inertia \(H = H/4\). It can be seen that the proposed MOHBMO based PSS has good performance in damping low frequency oscillations and stabilizes the system quickly. Moreover, it is superior to the SPEA and classical based methods tuned stabilizer.
To demonstrate performance robustness of the proposed method, two performance indices: the Integral of the Time multiplied Absolute value of the Error (ITAE) and Figure of Merit (FD) based on the system performance characteristics are defined as [17]:

$$\text{ITAE} = 1000 \times \int_t |\Delta \omega| dt$$

$$\text{FD} = 10 \times [(500 \times \text{OS})^2 + (8000 \times \text{US})^2 + 0.01 \times T_d^2]$$ \hspace{1cm} (10)

Where, Overshoot (OS), Undershoot (US) and settling time of rotor angle deviation of machine is considered for evaluation of the FD. It is worth mentioning that the lower the value of these indices is, the better the system response in terms of time-domain characteristics. Numerical results of performance robustness for all cases as given in Table 1 for scenario 1 are listed in Table 3, respectively.

<table>
<thead>
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<th>Case No</th>
<th>MOHBMO</th>
<th>SPEA</th>
<th>Classic</th>
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<tr>
<td></td>
<td>ITAE</td>
<td>FD</td>
<td>ITAE</td>
</tr>
<tr>
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<td>0.6775</td>
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It can be seen that the values of these system performance characteristics with the proposed MOHBMO based tuned PSSs are much smaller compared to that SPEA and classical based designed PSS. This demonstrates that the overshoot, undershoot settling time and speed deviations of machine is greatly reduced by applying the proposed MOHBMO based tuned PSS.

6. Conclusions
An attempt has been made in this paper to develop a simple but robust PSS with particular emphasis on achieving a minimum closed loop performance over a wide range of operating and system conditions. For dealing with different solutions in multi-objective optimization problem, Pareto dominance concept is used to generate and sort the dominated and non-dominated solutions. The minimum performance requirements of the stabilizer have been decided and this performance has been obtained using Fuzzified multi objective honey bee mating optimization. The nonlinear simulation results under wide range of operating conditions show the superiority and robustness of the Fuzzified multi objective HBMO method for the PSS design and their ability to provide efficient damping of low frequency oscillations in comparison with SPEA and classical methods. The effectiveness of the proposed method is tested on SMIB power system for a wide range of load demands and disturbances under different operating conditions. The nonlinear time simulation results confirm that the proposed MOHBMO based tuned PSS can work effectively over a wide range of loading conditions and is superior to the SPEA based tuned PSS and CPSS.

Appendix: System data
Generator: \( R_a = 0, \ x_d = 2.0, \ x_q = 1.91, \ x'_d = 0.244, \ x'_q = 0.244, \ f = 50 \text{ Hz}, \ T_d = 4.18, \ T_q = 0.75, \ H = 3.25 \)
Transmission line: \( R = 0, \ x_c = 0.3 \)
Exciter: \( K_e = 50, \ T_e = 0.05, \ E_{fdmax} = 7.0, \ E_{fdmin} = -7.0 \)

References


