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LFC DESIGN USING HBMO TECHNIQUE IN INTERCONNECTED POWER SYSTEM

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Abstract- A Honey Bee Mating Optimization (HBMO) algorithm is proposed to tune optimal gains of a Proportional Integral Derivative (PID) controller for Load Frequency Control (LFC) design in an interconnected power system in this paper. The problem of robustly tuning of PID based LFC design is formulated as an optimization problem according to the time domain-based objective function which is solved by the HBMO technique that has a strong ability to find the most optimistic results. To ensure performance and robustness of the proposed control strategy to stabilize frequency oscillations, the design process takes a wide range of operating conditions and system nonlinearities into account. To demonstrate the effectiveness of the proposed method a two-area interconnected power system is considered as a test system under different operating conditions. The simulation results are shown to maintain robust performance in comparison with the particle swarm optimization based tuned PID controller and classical controllers through ITAE performance indices. Results evaluation show that the proposed control strategy achieves good robust performance for wide range of system parameters and load changes in the presence of system nonlinearities and is superior to the other controllers. Moreover, the proposed control strategy has simple structure, easy to implement and tune which can be useful for the real world complex power system.

Keywords: LFC, HBMO, Power System Stability, PID Control Design.

I. INTRODUCTION

Load Frequency Control (LFC) is one of the most importance issues in electric power system design and operation. The objective of the LFC in an interconnected power system is to maintain the frequency of each area and to keep tie-line power near to the scheduled values by adjusting the MW outputs the LFC generators so as to accommodate fluctuating load demands. The LFC problem has been dealt with extensively for more than four decades. A comprehensive literatures review about the earlier studied in the field of LFC problem has been presented by Shayeghi et. al [1].

The availability of an accurate model of the system under study plays a crucial role in the development of the most control strategies like optimal control. However, an industrial process, such as a power system, contains different kinds of uncertainties due to changes in system parameters and characteristics, loads variation and errors in the modeling. On the other hand, the operating points of a power system may change very much randomly during a daily cycle. Because of this, a fixed controller based on classical theory is certainly not suitable for LFC problem. Thus, some authors have suggested variable structure [2-3] and neural networks methods [4-5] for dealing with parameter variations. All the proposed methods are based on state-space approach and require information about the system states, which are not usually known or available.

On the other hand, various adaptive techniques [6-7] have been introduced for LFC controller design. Due to requirement of the prefect model, which has to track the state variables and satisfy system constraints, it is rather difficult to apply these adaptive control techniques to LFC in practical implementations. Recently, several authors have been applied robust control methodologies [8-10] for the solution of LFC problem. Although via these methods, the uncertainties are directly introduced to the synthesis. But models of large scalar power system have several features that preclude direct application of robust control methodologies. Among these proper-ties, the most prominent are: very large (and unknown) model order, uncertain connection between subsystems, broad parameter variation and elaborate organizational structure.

Despite the potential of the modern control techniques with different structure, Proportional Integral Derivative (PID) type controller is still widely used for solution of the LFC problem [11-13]. This is because it performs well for a wide class of process. Also, they give robust performance for a wide range of operating conditions and easy to implement. The PID (PI) controller parameters tuning are usually done by trial and error methods based on the conventional experiences. Hence, they are not my capable of provide good robust performance for power system subjected to different kinds of uncertainties and disturbances. On the other hand, Goshal [11] have presented a comprehensive analysis of the effects of the different PID controller parameters on the overall dynamic performance of the LFC problem. It is shown that the appropriate selection of PID controller parameters results in satisfactory performance during system upsets. Thus, the optimal tuning of a PID gains is required to get the desired level of robust performance.

Recently, global optimization techniques like Genetic Algorithms (GA), Particle Swarm Optimization (PSO) and Simulated Annealing (SA) [14-16] have been applied for optimal tuning of PID based LFC schemes. These evolutionary algorithms are heuristic population-based search procedures that incorporate random variation and selection operators. Although, these methods seem to be good methods for the solution of PID parameter optimization problem, However, when the system has a highly epistatic objective function (i.e. where parameters being optimized are highly correlated), and number of parameters to be optimized is large, then they have degraded efficiency to obtain global optimum solution. In order to overcome these drawbacks, a Honey Bee Mating Optimization (HBMO) based PID type controller is proposed for solution of the LFC problem in this paper.

Here, HBMO technique is used for optimal tuning of PID parameter to improve optimization synthesis and damping of frequency oscillations. The HBMO algorithm is a typical swarm-based approach to optimization, in which the search algorithm is inspired by the honey-bee mating process [17] and has emerged as a useful tool for engineering optimization. It is a hybrid evolutionary algorithm which is comprised of GA, SA, local search, and some innovations for its self-adaptation. Unlike the other heuristic techniques, The HBMO algorithm has a flexible and well-balanced mechanism to enhance the global and local exploration abilities [18].

The effectiveness of the proposed controller is demonstrated through time domain simulation studies to damp frequency oscillations under different operating conditions and system nonlinearities. Results evaluation show that the HBMO based tuned damping controller achieves good robust performance for a wide range of plant parameters changes even in the presence of Generation Rate Constraints (GRC) and is superior to the designed controller using PSO technique [15] and classical controllers.

II. PLANT MODEL

A The LFC problem has been dealt with extensively for more than four decades. A comprehensive litratures review about the earlier studied in the field of LFC problem has been presented by Shayeghi et. al [1]. The power systems are usually large-scale systems with complex nonlinear dynamics. However, the major part of the work reported so far has been performed by considering lineanized models of two/multi area power systems. In advanced control strategies (such as the one considered in this paper) the error caused by simplification and linearization are considered as parametric uncertainties. A two-area power system is taken as test system in this study. In each area, all generators are assumed to be coherent group. Figure 1 shows the block diagram of the system in detail. The nomenclature used and the nominal parameter values are given in [15].

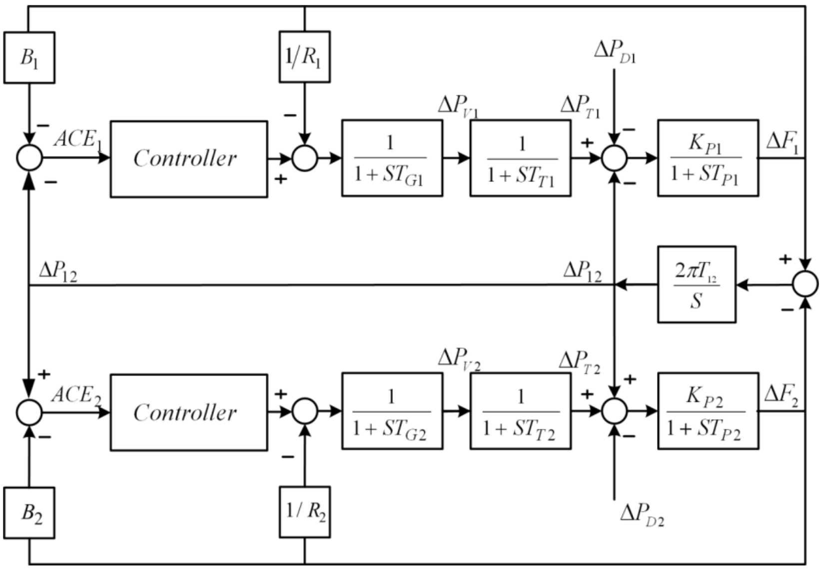

Figure. 1. Block diagram of a two-area power system

The small signal analysis is justified for studying the systems response for small perturbation one. However, the implementation of LFC strategy based on a linearized model on an essentially nonlinear system does not necessarily ensure the stability of the systems [9]. It was shown that the GDB nonlinearity tends to produce continuous oscillations in the area frequency and tie-line power transient response. Figure 2 shows the nonlinear model of governor for consideration GDB. The governor dead-bound effects that are important for speed control under small disturbances are considered to be 0.06% [9].

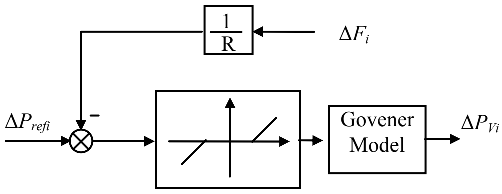

Figure 2. A nonlinear model of governor with GDB

One of the importance constraints in the LFC problem is GRC, i.e. practical limit on the rate of change in the generation power of each generator. The results in [19, 20] indicated that GRC would influence the dynamic responses of the system significantly and lead to larger overshot and longer settling time. In order to take effect of the GRC into account, the linear model of turbine $\Delta PV_i/\Delta PT_i$ in Figure 1 is usually replaced by a nonlinear model of Figure 3 (with $\pm\delta$ limit). Also, a limiter, bounded by $\pm\delta$ limit was used within the PID controller for governor system to prevent the excessive control action. In this study, δ is considered to be 0.015 [15].

In summary, The LFC goals for a power system are:

- Ensuring zero steady state error for frequency deviations.
- Minimizing unscheduled tie line power flows between neighboring control areas.
- Getting good tracking for load demands and disturbances.
- Maintaining acceptable overshoot and settling time on the frequency and tie-line power deviations

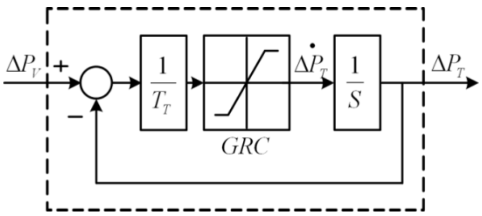

Figure 3. Nonlinear turbine model with GRC

Based on the above objectives, a control signal made up of tie line power flow deviation added to frequency deviation weighted by a bias factor called ACE is used as the control signal in the LFC problem. ACE serves to indicate when total generation must be raised or lowered in a control area.

By taking ACE_i as the system output, the PID controller transfer function in each control area over a given time interval s in Laplace domain is defined by, $(-G_i(s)ACE_i(s))$, where $G(s)$ is in:

$$G_i(s) = K_{Pi} + \frac{K_{Ii}}{s} + K_{Di}s \tag{1}$$

where, K_P is the proportional gain, K_I is the integral gain and K_D is the derivative gain.

It should be note that due to innumerable on-off switching operations in the customer side, the measurements of systems frequency and tie-lines power flow are usually deteriorated by noise. In this case, the noise is greatly amplified in magnitude by differential term of the PID controller. For this reason, a low-pass filter is added to differential feedback loop serially to solve the noise problem and practical implementation as follows:

$$G_i(s) = K_{Pi} + \frac{K_{Ii}}{s} + \frac{K_{Di}s}{1+\tau_{Di}s} \tag{2}$$

where, $|\tau_{Di}| << 1$ and usually is considered $K_{Di}/100$.

LFC goals, i.e. frequency regulation and tracking the load demands, maintaining the tie-line power interchanges to specified values in the presence of modeling uncertainties, system nonlinearities and area load disturbances determines the LFC synthesis as a multi-objective optimization problem. For this reason, the idea of HBMO technique, which gives a powerful optimization algorithm, is used to optimal tune of PID controllers in each control area.

III. HBMO ALGORITHM

A honey-bee colony typically consists of a single egg laying long-lived queen, several thousand drones (depending on the season), and workers and is a large family of bees living in one bee-hive and usually contains 10000 to 60000 workers [21-22]. Each bee undertakes sequences of actions which unfold according to genetic, ecological and social condition of the colony. Workers utilize some heuristic mechanisms such as crossover. Also any colony maybe contain one or much queen in it life's. In the marriage process, the queens mate during their mating flights far from the nest. 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 [17-18].

The HBMO algorithm starts with random generation of a set of initial solutions according to Figure 4. 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 [17]:

$$\text{prob}(Q,D) = e^{\frac{-\Delta(f)}{S(t)}} \tag{3}$$

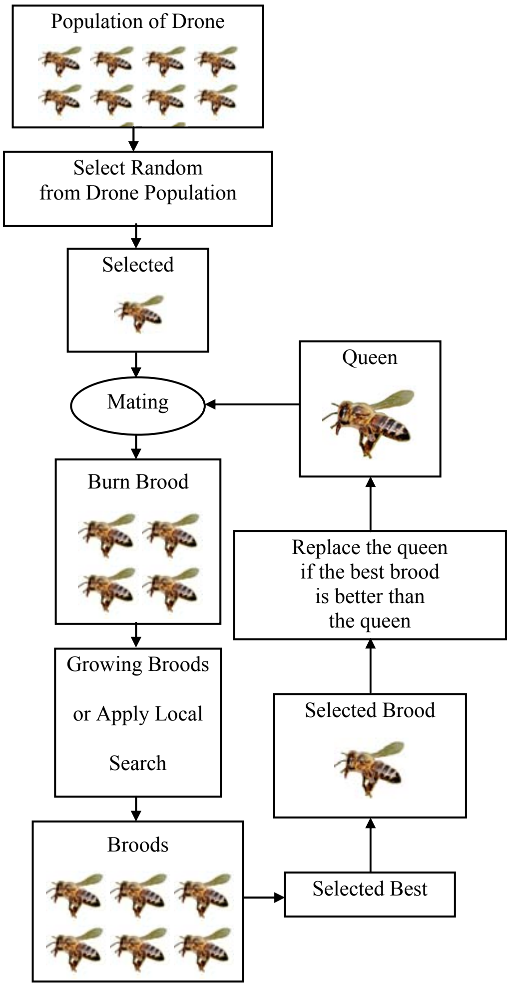

Figure 4. The proposed HBMO technique

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:

$$S(t+1) = \alpha \times S(t) \tag{4}$$

$$E(t+1) = E(t) - \gamma \tag{5}$$

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

In order to develop the algorithm, the capability of workers is restrained in brood care and thus each worker may be regarded as a heuristic that acts to improve and/or take care of a set of broods. The rate of improvement in the brood's genotype, defines the heuristic fitness value.

The fitness of the resulting genotype is determined by evaluating the value of the objective function of the brood genotype and/or its normalized value. It is important to note that a brood has only one genotype.

In general, the whole process of HBMO algorithm as shown in Figure 4 can be summarized at the five main steps as follows:

i) *Generate the initial drone sets and queen*: The algorithm starts with the mating flight, where a queen (best solution) selects drones probabilistically to form the spermatheca (list of drones). A drone then selected from the list randomly for the creation of broods.

ii) *Flight matting*: This step do the flight matting of queen Q. The best drone D_k with the largest prob(Q, D) among the drone set D is selected the object of matting for the queen Q. After the flight matting the queen's speed and energy decay is reduced by Equation (4). The flight matting is continues until the speed $S(t)$ is less than a threshold d or the number of sperms of the queen's spermatheca is less than the one threshold.

iii) Breeding process: In this step, a population of broods is generated based on matting between the queen and the drones stored in the queen's spermatheca. The breeding process can transfer the genes of drones and the queen to the j-th individual based on the Equation (6).

$$child = parent_1 + \beta(parent_2 - parent_1) \tag{6}$$

where β is the decreasing factor ($\beta \in [0,1]$).

iv) *Adaptation of worker's fitness*: The population of broods is improved by applying the mutation operators as follows:

$$Brood_i^k = Brood_i^k \pm (\delta + \varepsilon) Brood_i^k \\ \delta \in [0,1], 0 < \varepsilon < 1 \tag{7}$$

The δ is randomly generated and ε is predefined. The best brood ($Brood_{best}$) with maximum objective function value is selected as the candidate queen. If the objective function of $Brood_{best}$ is superior to the queen, the queen replace with $Brood_{best}$.

v) *Check the termination criteria:* If the termination criteria satisfied finish the algorithm, else generate new drones set and go to step 2.

The algorithm continues with three user-defined parameters and one predefined parameter. The predefined parameter is the number of workers (W), representing the number of heuristics encoded in the program [17, 22]. The user-defined parameters are number of queens, the queen's spermatheca size representing the maximum number of mating per queen in a single mating flight and the number of broods that will be borne by all queens. The speed of each queen at the start of each mating flight initialized at randomly. As this algorithm is combination of simulated annealing, genetic operator and swarm intelligence it is very interesting optimization algorithm that used in optimization problems of reservoir operation.

IV. HBMO-BASED PID TYPE LFC

In this study, PID controller is used for the solution of LFC problem. This is because it used in almost all sectors of industry and science such as power systems, easy to implement and familiar to engineers [12, 16]. It should be noted that the transient performance of the power system with respect to the control of the frequency and tie-line power flows obviously depends on the optimal tuning of the PID controller's parameters. On the other hand, the conventional methods to tune PID gains not able to locate or identify the global optimum for achieving the desired level of system robust performance due to the complexity and multi-variable conditions of the power systems and also they may be tedious and time consuming.

In order to overcome these drawbacks and provide optimal control performance, the HBMO algorithm is proposed to optimal tune of PID gains under different operating conditions. Figure 5 shows the block diagram of HBMO based tuned PID controller to solve the LFC problem for each control area (Figure 1).

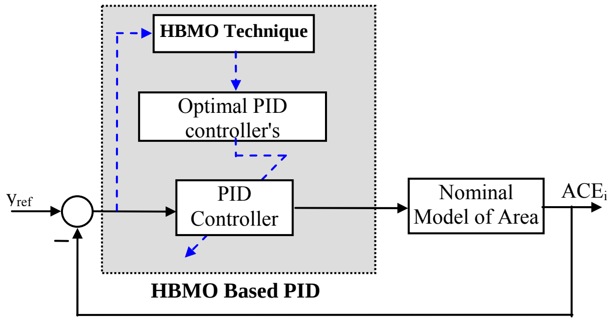

Figure 5. The proposed HBMO based PID controller structure.

The gains of PID controllers are tuned using HBMO technique and then, the PID controller generates the control signal that applies to the governor set point in each area. In this study, the HBMO module works offline.

Simulation results and eigenvalue analysis show that the open loop system performance is affected more significantly by changing in the K_{pi}, T_{pi}, B_i and T_{ij} than changes of other parameters [23]. Thus, to illustrate the capability of the proposed strategy, in the view point of uncertainty our focus will be concentrated on variation of these parameters. It should be noted that choice of the properly objective function is very important in synthesis procedure for achieving the desired level of system robust performance. Because different objective functions promote different HBMO behaviors, which generate fitness value providing a performance measure of the problem considered. For our optimization problem, an Integral of Time multiplied Absolute value of the Error (ITAE) is taken as the objective function. The objective function is defined as follows:

$$J = \max\left\{ITAE^{p=-\%30}, ITAE^{p=-\%20}, \ldots, ITAE^{p=+\%30}\right\}$$
$$ITAE^{p} = \sum_{i=1}^{N}\int_{0}^{t=tsim} t\left|ACE_i\right|dt \tag{8}$$

where, t_{sim} is the time range of simulation; N is the number of area control in power systems and p is percent value of the uncertain plant parameters changes from the nominal values for which the optimization is carried out. It is aimed to minimize this objective function in order to improve the system response in terms of the settling time and overshoots. The design problem can be formulated as the following constrained optimization problem, where the constraints are the PID controller parameter bounds.

Minimize J Subject to

$$K_{Pi}^{\min} \le K_{Pi} \le K_{Pi}^{\max}$$
$$K_{Ii}^{\min} \le K_{Ii} \le K_{Ii}^{\max} \tag{9}$$
$$K_{Di}^{\min} \le K_{Di} \le K_{Di}^{\max}$$

Typical ranges of the optimized parameters are [0.01-20]. To improve the overall system dynamical performance in a robust way and optimization synthesis, this paper employs HBMO technique to solve the above optimization problem and search for optimal or near optimal set of PID controller parameters (K_{Pi}, K_{Ii} and K_{Di} for i=1, 2 ,..., N).

The optimization of PID controller parameters is carried out by evaluating the objective cost function as given in Equation (9), which considers a multiple of operating conditions by applying a step load change 0.01 p.u. MW to one area. The operating conditions are considered with variation uncertain plant parameters of K_{pi}, T_{pi}, B_i and T_{ij} from -30% to 30% of the nominal values by 10% step (i.e. 7 operating points). In this study, in order to acquire better performance, number of queens, drones, broods, workers, the queen's spermatheca size, α, β, γ and ε is chosen as 6, 50, 10, 10, 10000, 0.9, 0.8, and 0.92 and 0.4, respectively. It should be noted that HBMO algorithm is run several times and then optimal set of PID controller parameters is selected. The final values of the optimized parameters with objective function, J, using the HBMO and PSO techniques [15] are given in Table 1.

Table 1. Optimized parameters of PID controller

	k_{P1}	k_{I1}	k_{D1}	k_{P1}	k_{I2}	k_{D2}
HBMO	2.2	1.02	1.23	2.2	1.02	1.23
PSO	2.95	1.35	1.02	2.95	1.35	1.02

V. SIMULATION RESULTS

The test system for LFC as shown in Figure 1 consists of two areas control. The performance of the proposed HMBO based tuned PID controller (HBMOPID) is compared with the proposed methods in [15] and conventional controllers for two cases of the plant parameters changes and load disturbances to illustrate its robust performance in the presence of GRC and GDB effects as discussed in section two.

- Case 1: We will test the system performance with nominal parameters. We choose the nominal parameters as given in Appendix A and apply load changes of $\Delta P_{d1}(t)$=0.01 p.u. MW to one area. The responses of ΔF_1(t) and ΔP_{tie}(t) are shown in Figure 6. From these results, it can be seen that the frequency and tie-line power deviations effectively damped to zero with HMBO based tuned PID controller than the other controllers.

- Case 2: In this case, the closed loop performance is tested in the presence of both step load demands and uncertainties. It is assumed that a step load 0.015 and 0.005 pu MW is demanded by one and two areas. Power system responses with 30% decrease and increase in uncertain parameters K_{Pi}, T_{Pi}, B_i and T_{ij} are depicted in Figures 7 and 8, respectively. The simulation results indicated that the proposed control strategy can grantees the stability of the overall system and achieves good performance even in the presence of GRC and GDB.

To demonstrate performance robustness of the proposed method, the two indices: $ITAE$ and Figure of Demerit (FD) based on the system performance characteristics are being used as:

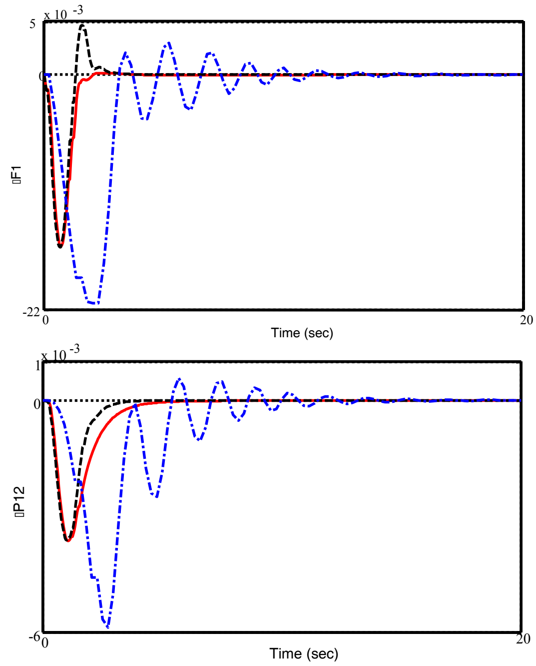

Figure 6. The performance of the controllers for the case 1; Solid (HBMOPID), Dashed [15], Dashed-dotted (Integral)

$$ITAE(\Delta f) = 150 \times \left(\int_0^{20\sec} \left| \Delta f_1^1 \right| tdt \right)$$
$$ITAE(\Delta P) = 150 \times \left(\int_0^{20\sec} \left| \Delta P_{12}^1 \right| tdt \right) \quad (10)$$

$$FD = (OS \times 20)^2 + (US \times 5)^2 + Ts^2 \quad (11)$$

where, Overshoot (OS), Undershoot (US) and settling time (for 1% band of the total load demand in area 1) of frequency deviation area 1 is considered for evaluation of the FD. The values of $ITAE$ and FD are calculated by applying a step load changes 0.01 p.u. MW to one area, whereas the system parameters are varied from -30% to 30% of the nominal values. Tables 2-4 show the values of ITAE and FD for different operation conditions with four control schemes. Examination of this Table reveals that the proposed control strategy achieves good robust performance against parametric uncertainties and system nonlinearities.

Table 2. $ITAE$ value for Δf_1

Parameter percent changes	$ITAE(\Delta f)$		
	Classic	PSO	HBMO
30%	214.85	2.77	2.10
25%	142.96	2.69	2.03
20%	93.56	2.37	1.94
15%	60.75	2.30	1.83
10%	42.04	2.22	1.69
5%	37.23	2.11	1.70
Nominal	22.23	1.97	1.71
-5%	18.36	2.04	1.77
-10%	14.57	2.23	2.09
-15%	15.03	2.53	2.58
-20%	14.99	2.78	3.22
-25%	15.84	3.24	3.32
-30%	18.00	3.73	3.55

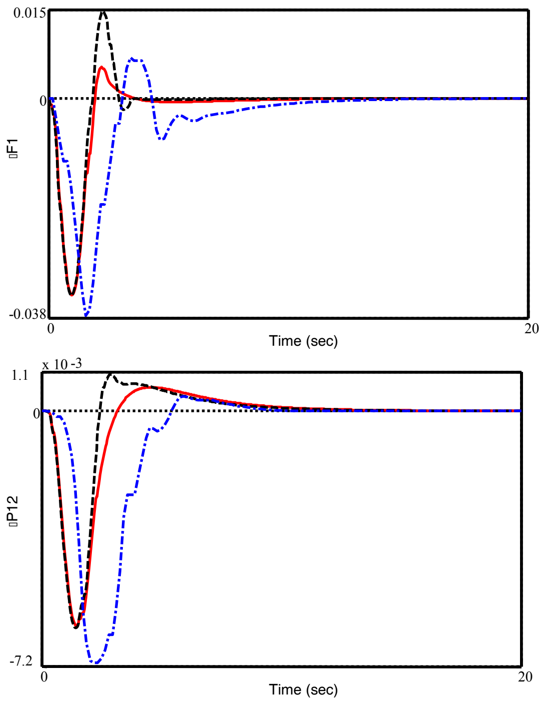

Figure. 7. The performance of the controllers for the case 2; Solid (HBMOPID), Dashed [15], Dashed-dotted (Integral)

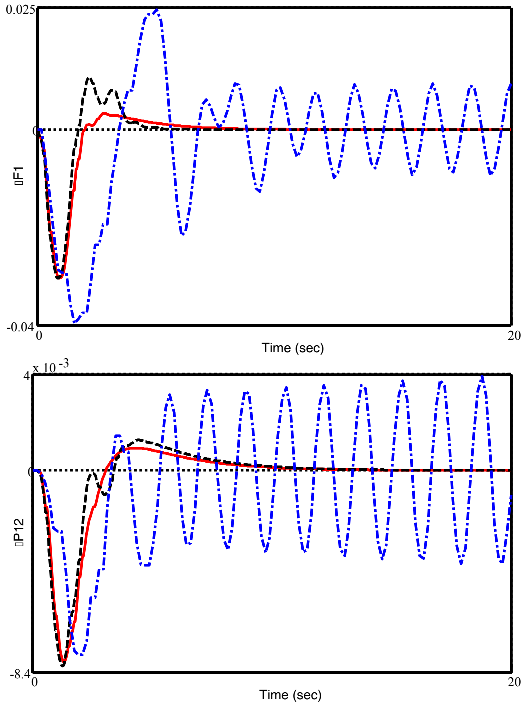

Figure. 8. The performance of the controllers for the case 2; Solid (HBMOPID), Dashed [15], Dashed-dotted (Integral)

VI. CONCLUSIONS

One of the important problems in LFC task is designing a suitable controller to get a desire level of robust performance against parametric uncertainties and system nonlinearities. For this reason, the Honey bee mating optimization algorithm has been successfully applied to the robust design of PID controllers for solution of the LFC problem.

Table 3. *ITAE* value for ΔP

Parameter percent changes	$ITAE(\Delta P)$		
	Classic	PSO	HBMO
30%	94.77	1.00	1.30
25%	60.75	0.97	1.27
20%	38.04	0.82	1.22
15%	23.84	0.81	1.20
10%	15.77	0.77	1.18
5%	12.50	0.75	1.26
Nominal	7.49	0.74	1.29
-5%	6.12	0.77	1.29
-10%	5.00	0.80	1.34
-15%	4.80	0.84	1.43
-20%	4.44	0.85	1.53
-25%	4.37	0.89	1.56
-30%	4.55	0.89	1.61

Table 4. *FD* value

Parameter percent changes	$ITAE(\Delta P)$	
	PSO	HBMO
30%	277.2644	245.0426
25%	279.8038	247.8038
20%	282.0780	251.1352
15%	284.8408	254.0223
10%	287.6093	257.5691
5%	290.2526	261.0962
Nominal	292.2442	264.0230
-5%	293.1485	266.9106
-10%	295.9698	270.3509
-15%	299.2767	274.1264
-20%	302.7073	278.2564
-25%	305.9634	282.1154
-30%	308.9939	285.7750

The design problem of the robustly selecting controller parameters is converted into an optimization problem according to time domain-based objective function over a wide range of operating conditions which is solved by a HBMO technique. It is a novel swarm based hybrid evolutionary search technique and combines the advantages of GA, SA, local search, and some innovations for its self-adaptation. Thus, it has stronger global search ability and more robust than PSO and other heuristic methods.

The effectiveness of the proposed strategy was tested on a two-area power system under possible contracts with various load changes in the presence of modeling uncertainties, GDB and GRC. The simulation results show that the proposed HMBO based tuned PID controller achieves good robust performance for a wide range of system parameters and is superior to PSO based tuned PID and convention controller. The system performance characteristics in terms of '*ITAE*' indices reveal that the proposed robust PID type tuned controller is a promising control scheme for the solution of the LFC problem. Moreover, the proposed control strategy has simple structure, easy to implement and tune and therefore it is recommended to generate good quality and reliable electric energy in the interconnected power systems.

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