International Journal on
"Technical and Physical Problems of Engineering"
(IJTPE)
Published by International Organization on TPE (IOTPE)

ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com

March 2011 Issue 6 Volume 3 Number 1 Pages 1-10

MARKET BASED LFC DESIGN USING ARTIFICIAL BEE COLONY

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Abstract- Proportional Integral Derivative (PID) type controller is still widely used for the solution of the Load Frequency Control (LFC) problem. On the other hand, the optimal tuning of PID gains is required to get the desired level of robust performance under different operation conditions. In this paper, optimal gains tuning of a PID controller for solution of the LFC problem in the restructured power system is proposed using Artificial Bee Colony (ABC) algorithm. 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 ABC 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 restructured 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 and genetic algorithm based tuned PID controllers through FD and 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 restructured power system.

Keywords: Load Frequency Control, ABC, Restructured Power System, PID Control, PSO.

I. INTRODUCTION

Global analysis of the power system markets shows that the frequency control is one of the most profitable ancillary services at these systems. This service is related to the short-term balance of energy and frequency of the power systems. The most common methods used to accomplish frequency control are generator governor response (primary frequency regulation) and load frequency control (LFC). The goal of LFC is to reestablish primary frequency regulation capacity, return the frequency to its nominal value and minimize unscheduled tie-line power flows between neighboring control areas [1]. The main goal of the LFC is to maintain zero steady state errors for frequency deviation and good tracking load demands in a multi-area restructured power system.

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 applied robust control methodologies [8-10] for solution of LFC problem. In 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. In these properties, 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, Shayeghi et. al [11] have presented a comprehensive analysis of the effects of the different PID controller parameters on 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. Since optimal setting of PID controller gains is a "multimodal" optimization problem (i.e., there exists more than one local optimum) and more complex due to nonlinearity, complexity and time-variability of the real world power systems operation. Hence, local optimization techniques, which are well elaborated upon, are not suitable for such a problem. Moreover, there is no local criterion to decide whether a local solution is also the global solution. Thus, the conventional optimization methods that make use of derivatives and gradients are, in general, not able to locate or identify the global optimum, but for real-world applications, one is often content with a "good" solution, even if it is not the best. Consequently, heuristic methods are widely used for global optimization problems.

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, an Artificial Bee Colony (ABC) algorithm based PID type controller is proposed for solution of the LFC problem in this paper. Here, ABC optimization algorithm is used for optimal tuning of PID parameter to improve optimization synthesis and damping of frequency oscillations.

The ABC algorithm which is one of the most recently introduced optimization algorithm, simulates the intelligent foraging behavior of a honey bee swarm. It incorporates a flexible and well-balanced mechanism to adapt to the global and local exploration and exploitation abilities within a short computation time. Hence, this method is efficient in handling large and complex search spaces. Due to its simplicity and easy implementation, the ABC algorithm has captured much attention and has been applied to solve many practical optimization problems [17]. It has also been found to be robust in solving problems featuring non-linearity, non-differentiability and high dimensionality [18]. Compared with the usual algorithms, the major advantage of ABC algorithm lays in that it conducts both global search and local search in each iteration and as a result the probability of finding the optimal parameters is significantly increased, which efficiently avoid local optimum to a large extent.

In this study, the problem of robust PID based load frequency controller design is formulated as an optimization problem. The controller is automatically tuned with optimization a time domain based objective function by ABC such that the relative stability is guaranteed and the time domain specifications concurrently secured. The effectiveness of the proposed controller is demonstrated through time domain simulation studies and some performance indices to damp frequency oscillations under different operating conditions and system nonlinearities. Results evaluation show that the ABC 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 and GA techniques.

II. TWO-AREA DEREGULATED POWER SYSTEM

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]. Generalized dynamical for the LFC scheme has been developed in [19] based on the possible contracts in the deregulated environments. This section gives a brief overview on this generalized model. In the deregulated power system, Generation Companies (GENCOs) may or may not participate in the LFC task and Distribution Companies (DISCOs) have the liberty to contract with any available GENCOs in their own or other areas. Thus, there can be various combinations of the possible contracted scenarios between DISCOs and GENCOs. The concept of an Augmented Generation Participation Matrix (AGPM) is introduced to express these possible contracts in the generalized model. The rows and columns of AGPM is equal with the total number of GENCOs and DISCOs in the overall power system, respectively. For example, the AGPM structure for a large scale power system with N control area is given by:

$$AGPM_{ij} = \begin{bmatrix} gpf_{(s_i+1)(z_j+1)} & \cdots & gpf_{(s_i+1)(z_j+m_j)} \\ \vdots & \ddots & \vdots \\ gpf_{(s_i+n_i)(z_j+1)} & \cdots & gpf_{(s_i+n_i)(z_j+m_j)} \end{bmatrix} \tag{1}$$

where,

$$AGPM_{ij} = \begin{bmatrix} gpf_{(s_i+1)(z_j+1)} & \cdots & gpf_{(s_i+1)(z_j+m_j)} \\ \vdots & \ddots & \vdots \\ gpf_{(s_i+n_i)(z_j+1)} & \cdots & gpf_{(s_i+n_i)(z_j+m_j)} \end{bmatrix}$$

for $i, j=1,\ldots,N$ and

$$s_i = \sum_{k=1}^{i-1} n_i \,,\; z_j = \sum_{k=1}^{j-1} m_j \,, \quad s_1 = z_1 = 0$$

where, n_i and m_i are the number of GENCOs and DISCOs in area i and gpf_{ij} refer to "generation participation factor" and shows the participation factor GENCO i in total load following requirement of DISCO j based on the possible contract. The sum of all entries in each column of AGPM is unity. To illustrate the effectiveness of the modeling strategy and proposed control design, a three control area power system is considered as a test system. It is assumed that each control area includes two GENCOs and a DISCO. Block diagram of the generalized LFC scheme for test power system is shown in Figure 1. The power system parameters are given in Appendices.

The dotted and dashed lines show the demand signals based on the possible contracts between GENCOs and DISCOs which carry information as to which GENCO has to follow a load demanded by which DISCO. These new information signals were absent in the traditional LFC scheme. As there are many GENCOs in each area, ACE signal has to be distributed among them due to their ACE participation factor in the LFC task and $\sum_{j=1}^{n_i} apf_{ji} = 1$. We can write [19]:

$$d_i = \Delta P_{Loc,j} + \Delta P_{di},\ \Delta P_{Loc,j} = \sum_{j=1}^{m_i} \Delta P_{Lj-i},\ \Delta P_{di} = \sum_{j=1}^{m_i} \Delta P_{ULj-i} \quad (2)$$

$$\eta_i = \sum_{j=1\&j\neq i}^{N} T_{ij}\Delta f_j \quad (3)$$

$$\zeta_i = \Delta P_{tie,i,sch} = \sum_{k=1\&k\neq i}^{N} \Delta P_{tie,ik,sch} \quad (4)$$

$$\Delta P_{tie,ik,sch} = \sum_{j=1}^{n_i}\sum_{t=1}^{m_k} gpf_{(s_i+j)(z_k+t)}\Delta P_{Lt-k} - \sum_{t=1}^{n_k}\sum_{j=1}^{m_i} gpf_{(s_k+t)(z_i+j)}\Delta P_{Lj-i} \quad (5)$$

$$\rho_i = [\rho_{1i} \ \cdots \ \rho_{ki} \ \cdots \ \rho_{n_i i}]$$
$$\rho_{ki} = \sum_{j=1}^{N}[\sum_{t=1}^{m_j} gpf_{(s_i+k)(z_j+t)}\Delta P_{Lt-j}] \quad (6)$$

$$\Delta P_{m,k-i} = \rho_{ki} + apf_{ki}\Delta P_{di} \quad (7)$$

where, $\Delta P_{m,ki}$ is the desired total power generation of a GENCO k in area i and must track the demand of the DISCOs in contract with it in the steady state.

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 [13, 21] 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 2 (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 0.2 [15].

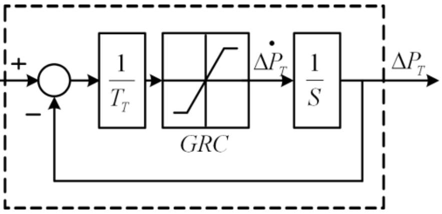

Figure 2. Nonlinear turbine

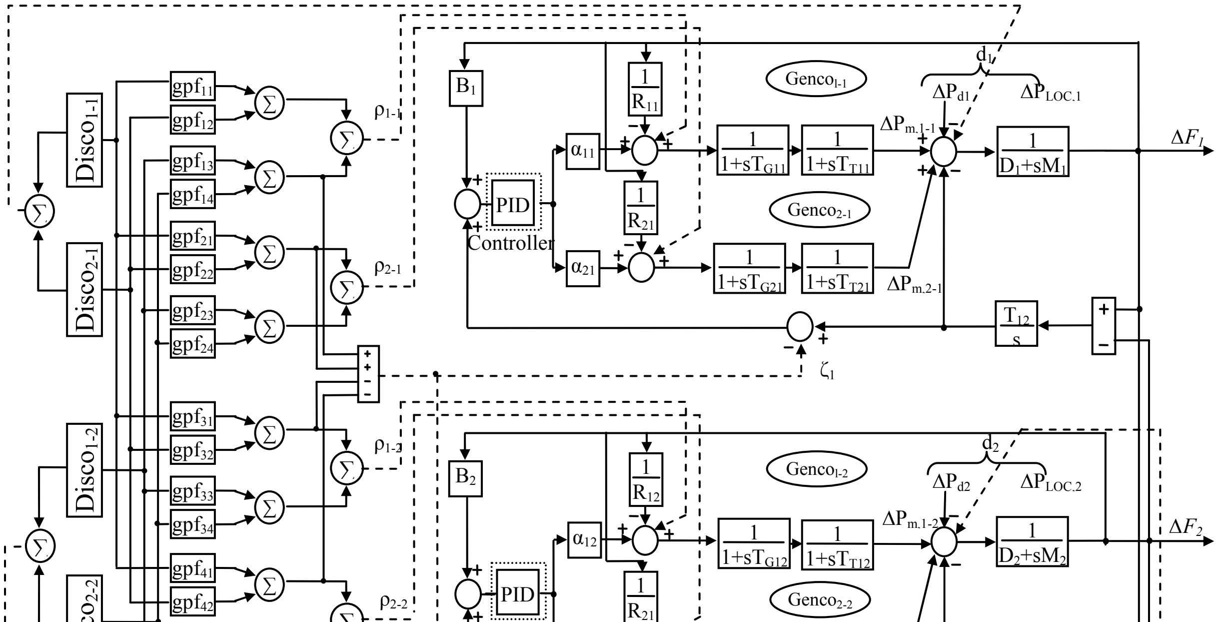

Figure 1. The generalized LFC scheme in the restructured system

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

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:

$$G_i(s) = K_{Pi} + \frac{K_{Ii}}{s} + K_{Di}s \tag{8}$$

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:

$$G_i(s) = K_{Pi} + \frac{K_{Ii}}{s} + \frac{K_{Di}s}{1+\tau_{Di}s} \tag{9}$$

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 ABC technique, which gives a powerful optimization algorithm, is used to optimal tune of PID controllers in each control area.

III. ABC ALGORITHM

Honey-bees are among the most closely studied social insets. Their foraging behavior, learning, memorizing and information sharing characteristics have recently been one of the most interesting research areas in swarm intelligence. Recently, Karaboga and Basturk [21] have described an Artificial Bee Colony (ABC) algorithm based on the foraging behavior of honey-bees for numerical optimization problems. The algorithm simulates the intelligent foraging behavior of honey bee swarms. It is a very simple, robust and population based stochastic optimization algorithm. Compared with the usual algorithms, the major advantage of ABC algorithm lays in that it conducts both global search and local search in each iteration, and as a result the probability of finding the optimal parameters is significantly increased, which efficiently avoid local optimum to a large extent.

In the ABC algorithm, the colony of artificial bees contains three groups of bees: employed bees, onlookers and scouts. A bee waiting on the dance area for making decision to choose a food source, is called an onlooker and a bee going to the food source visited by itself previously is named an employed bee. A bee carrying out random search is called a scout. Communication among bees about the quality of food sources is being achieved in the dancing area by performing waggle dance. In the ABC algorithm, first half of the colony consists of employed artificial bees and the second half constitutes the onlookers. In other words, the number of employed bees is equal to the number of food sources around the hive. The employed bee whose food source is exhausted by the employed and onlooker bees becomes a scout. The main steps of the algorithm are given below [22]:

- Initialize.
- REPEAT.

(a) Place the employed bees on the food sources in the memory;

(b) Place the onlooker bees on the food sources in the memory;

(c) Send the scouts to the search area for discovering new food sources.

- UNTIL (requirements are met).

In the ABC algorithm, each cycle of the search consists of three steps: sending the employed bees onto the food sources and then measuring their nectar amounts; selecting of the food sources by the onlookers after sharing the information of employed bees and determining the nectar amount of the foods; determining the scout bees and then sending them onto possible food sources.

The flowchart of the proposed ABC algorithm is shown in Figure 3. At the initialization stage, a set of food source positions are randomly selected by the bees and their nectar amounts are determined. Then, these bees come into the hive and share the nectar information of the sources with the bees waiting on the dance area within the hive. At the second stage, after sharing the information, every employed bee goes to the food source area visited by her at the previous cycle since that food source exists in her memory, and then chooses a new food source by means of visual information in the neighbourhood of the present one. At the third stage, an onlooker prefers a food source area depending on the nectar information distributed by the employed bees on the dance area. As the nectar amount of a food source increases, the probability with which that food source is chosen by an onlooker increases, too. Hence, the dance of employed bees carrying higher nectar recruits the onlookers for the food source areas with higher nectar amount. After arriving at the selected area, she chooses a new food source in the neighbourhood of the one in the memory depending on visual information. Visual information is based on the comparison of food source positions. When the nectar of a food source is abandoned by the bees, a new food source is randomly determined by a scout bee and replaced with the abandoned one. In the proposed model, at each cycle at most one scout goes outside for searching a new food source and the number of employed and onlooker bees were equal. In the ABC algorithm, the position of a food source represents a possible solution of the optimization problem and the nectar amount of a food source corresponds to the quality (fitness) of the associated solution. The number of the employed bees or the onlooker bees is equal to the number of solutions in the population.

At the first step, the ABC generates a randomly distributed initial population $P(G=0)$ of SN solutions (food source positions), where SN denotes the size of population. Each solution (food source) x_i ($i = 1, 2,..., SN$) is a D-dimensional vector. Here, D is the number of optimization parameters. After initialization, the population of the positions (solutions) is subjected to repeated cycles, $C = 1, 2,...,C_{\max}$, of the search processes of the employed bees, the onlooker bees and scout bees. An artificial employed or onlooker bee probabilistically produces a modification on the position (solution) in her memory for finding a new food source and tests the nectar amount (fitness value) of the new source (new solution). The artificial bees randomly select a food source position and produce a modification on the one existing in their memory as described in (4). Provided that the nectar amount of the new source is higher than that of the previous one the bee memorizes the new position and forgets the old one. Otherwise she keeps the position of the previous one.

After all employed bees complete the search process, they share the nectar information of the food sources (solutions) and their position information with the onlooker bees on the dance area. An onlooker bee evaluates the nectar information taken from all employed bees and chooses a food source with a probability related to its nectar amount. As in the case of the employed bee, she produces a modification on the position (solution) in her memory and checks the nectar amount of the candidate source (solution). Providing that its nectar is higher than that of the previous one, the bee memorizes the new position and forgets the old one.

An onlooker bee chooses a food source depending on the probability value associated with that food source, p_i, calculated by the following expression:

$$p_i = \frac{fit_i}{\sum_{n=1}^{SN} fit_n} \tag{10}$$

where fit_i is the fitness value of the solution i evaluated by its employed bee, which is proportional to the nectar amount of the food source in the position i and SN is the number of food sources which is equal to the number of employed bees (BN). In this way, the employed bees exchange their information with the onlookers. In order to produce a candidate food position from the old one, the ABC uses the following expression (11):

$$v_{ij} = x_{ij} + \phi_{ij}(x_{ij} - x_{kj}) \tag{11}$$

where, $k \in \{1, 2, ..., BN\}$ and $j \in \{1, 2, ..., D\}$ are randomly chosen indexes. Although k is determined randomly, it has to be different from i. ϕ_{ij} is a random number between [−1, 1]. It controls the production of a neighbour food source position around x_{ij} and the modification represents the comparison of the neighbor food positions visually by the bee. Equation (11) shows that as the difference between the parameters of the x_{ij} and x_{kj} decreases, the perturbation on the position x_{ij} decreases, too. Thus, as the search approaches to the optimum solution in the search space, the step length is adaptively reduced. If a parameter produced by this operation exceeds its predetermined limit, the parameter can be set to an acceptable value. In this work, the value of the parameter exceeding its limit is set to its limit value.

The food source whose nectar is abandoned by the bees is replaced with a new food source by the scouts. In the ABC algorithm this is simulated by randomly producing a position and replacing it with the abandoned one. If a position cannot be improved further through a predetermined number of cycles called "limit" then that food source is assumed to be abandoned.

After each candidate source position v_{ij} is produced and then evaluated by the artificial bee, its performance is compared with that of x_{ij}. If the new food has equal or better nectar than the old source, it is replaced with the old one in the memory. Otherwise, the old one is retained. In other words, a greedy selection mechanism is employed as the selection operation between the old and the current food sources.

ABC algorithm in fact employs four different selection processes:

i) A global selection process used by the artificial onlooker bees for discovering promising regions as described by (10).

ii) A local selection process carried out in a region by the artificial employed bees and the onlookers depending on local information (in case of real bees, this information includes the color, shape and fragrance of the flowers) (bees will not be able to identify the type of nectar source until they arrive at the right location and discriminate among sources "growing" there based on their scent) for determining a neighbor food source around the source in the memory as defined in (11).

iii) A local selection process called greedy selection process carried out by all bees in that if the nectar amount of the candidate source is better than that of the present one, the bee forgets the present one and memorizes the candidate source. Otherwise, the bee keeps the present one in the memory.

iv) A random selection process carried out by scouts.

It is clear from the above explanation that there are three control parameters used in the basic ABC: The number of the food sources which is equal to the number of employed or onlooker bees (SN), the value of "limit" and the Maximum Cycle Number (MCN).

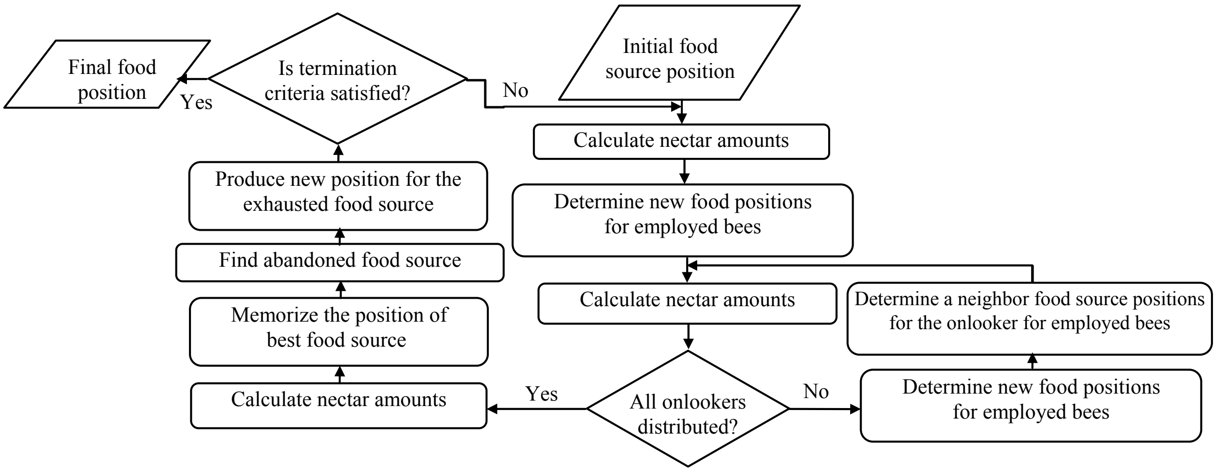

Figure 3. The flowchart of the proposed ABC algorithm

In the case of honey bees, the recruitment rate represents a “measure” of how quickly the bee colony finds and exploits a newly discovered food source. Artificial recruiting could similarly represent the “measurement” of the speed with which the feasible solutions or the “good quality” solutions of the difficult optimization problems can be discovered. The survival and progress of the bee colony are dependent upon the rapid discovery and efficient utilization of the best food resources. Similarly, the successful solution of difficult engineering problems is connected to the relatively fast discovery of “good solutions” especially for the problems that need to be solved in real time. In a robust search process, exploration and exploitation processes must be carried out together. In the ABC algorithm, while onlookers and employed bees carry out the exploitation process in the search space, the scouts control the exploration process.

IV. ABC BASED PID TYPE LFC

Nowadays, despite the significant developments of recent years in control theory and technology PID controllers are used in almost all sectors of industry and science such as power systems [12, 15]. This is because it performs well for a wide class of process. Also, they give robust performance for a wide range of operating conditions. Furthermore, they are easy to implement using analogue or digital hardware and familiar to engineers. In this study, PID controller is used for the solution of LFC problem. 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.

It is well know that 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, PSO algorithm is proposed to off-line optimal tune of PID gains under different operating conditions.

Figure 4 shows the block diagram of ABC based tuned PID controller to solve the LFC problem for each control area (Figure 1).

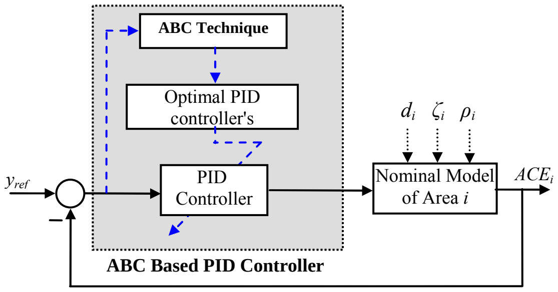

Figure 4. The proposed ABC based PID controller structure.

By taking ACE_i as the system output, the control vector for PID controller in each control area is given by:

$$u_i = K_{Pi}ACE_i + K_{Ii}\int ACE_i dt + K_{Di}\dot{ACE}_i \tag{12}$$

The gains K_{Pi}, K_{Ii} and K_{Di} are tuned using ABC technique and then, the PID controller generates the control signal that applies to the governor set point in each area. In this study, the ABC 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 ABC 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:

$$J = \max\left\{ITAE^{p=-\%30}, ITAE^{p=-\%20}, ..., ITAE^{p=+\%30}\right\} \tag{13}$$

$$ITAE^p = \sum_{i=1}^{N}\int_0^{t=tsim} t\left|ACE_i\right|dt \tag{14}$$

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 from nominal values for which the optimization is carried out. For objective function calculation, the time-domain simulation of the power system model is carried out for the simulation period. 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

$$\begin{aligned} K_{Pi}^{\min} &\le K_{Pi} \le K_{Pi}^{\max} \\ K_{Ii}^{\min} &\le K_{Ii} \le K_{Ii}^{\max} \\ K_{Di}^{\min} &\le K_{Di} \le K_{Di}^{\max} \end{aligned} \tag{15}$$

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 ABC 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 (15), which considers a multiple of operating conditions. Consider that all DISCOs contract with available GENCOs for power as per the following AGPM. All GENCOs participate in the LFC task.

$$AGPM_2 = \begin{bmatrix} 0.5 & 0.25 & 0 & 0.3 \\ 0.2 & 0.25 & 0 & 0 \\ 0 & 0.25 & 1 & 0.7 \\ 0.3 & 0.25 & 0 & 0 \end{bmatrix} \begin{matrix} apf_{11} = 0.75 \\ apf_{21} = 0.25 \\ apf_{12} = 0.5 \\ apf_{22} = 0.5 \end{matrix}$$

It is assume that a large step load 0.1 pu MW is demanded by each DISCOs in all areas. Moreover, consider that DISCOs of area 1 and 2 demands 0.05 and 0.03 pu MW of excess power, respectively, which is reflected as a local load perturbation of the areas. Under this contracted scenario, the operating conditions are obtained with variation system of K_{pi}, T_{pi}, B_i and T_{ij} from -25% to 25% of the nominal values by 5% step (i.e. 11 operating conditions). In this study, in order to acquire better performance, the number of the food sources, the value of "limit" and the MCN is chosen as 20, 8 and 100, 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 ABC, PSO [15] and GA techniques are given in Table 1.

Table 1. Optimized parameters of PID controller

Method	PID Gains					
	Area 1			Area 2		
	KP	*KI*	*KD*	*KP*	*KI*	*KD*
ABC	3.78	3.07	1.55	2.99	0.90	1.16
PSO	0.88	2.05	0.28	0.01	0.69	0.16
GA	1.1772	1.0523	0.2234	1.0791	0.5686	1.1032

V. SIMULATION RESULTS

The test system for LFC as shown in Figure 1 consists of two areas control, and its parameters are given in Appendices. The considered system is controlled by using:

1) the PSO based tuned PID controller (PSOPID) [13];
2) the GA based tuned PID controller (GAPID);
3) the ABC based PID controller designed according to the procedure described in section IV.

In the next, the performance of the proposed ABC based tuned PID controller (ABCPID) is compared with another three controllers for three cases of the plant parameters changes and load disturbances to illustrate its robust performance in the presence of GRC.

A. Scenario 1

In this scenario, the closed loop performance is tested in the presence of both step contracted load demands and uncertainties. A case of combined Poolco and bilateral based contracts between DISCOs and available GENCOs is considered based on the AGPM as given in pervious section. In this case, DISCOs have the freedom to have a contract with any GENCO in their or another areas. It is assumed that a large step load 0.1 pu MW is demanded by all DISCOs.

Moreover, consider that DISCOs of area 1 and 2 demands 0.05 and 0.03 pu MW of excess power, respectively, which is reflected as a local load perturbation of the areas. Based on the given AGPM all GENCOs participate in the LFC task.

Power system responses with 25% decrease in uncertain parameters K_{Pi}, T_{Pi}, B_i and T_{ij} are depicted in Figure 5. Using the proposed ABC based method, the frequency deviation of all areas is quickly driven back to zero and the tie-line power flows properly converges to the specified values in the steady state. i.e.: $\Delta P_{tie,\,12,sch}$=0.05 pu MW.

B. Scenario 2: Poolco Based Transactions

In this scenario, GENCOs participate only in the load following control of their areas. It is assumed that a large step load 0.1 pu is demanded by each DISCOs in areas 1 and 2. Assume that a case of Poolco based contracts between DISCOs and available GENCOs is simulated based on the following AGPM.

$$AGPM_1 = \begin{bmatrix} 0.4 & 0.6 & 0 & 0 \\ 0.6 & 0.4 & 0 & 0 \\ 0 & 0 & 0.5 & 0.5 \\ 0 & 0 & 0.5 & 0.5 \end{bmatrix} \begin{matrix} apf_{11} = 0.5 \\ apf_{21} = 0.5 \\ apf_{12} = 0.5 \\ apf_{22} = 0.5 \end{matrix}$$

The frequency deviation of two areas and tie-line power flow with 25% increase in system parameters are depicted in Figure 6. Using the proposed method, the frequency deviation of all areas and the tie-line power are quickly driven back to zero and has small overshoots (Figure 6). Since there are no contracts between areas, the scheduled steady state power flows, over the tie-line are zero.

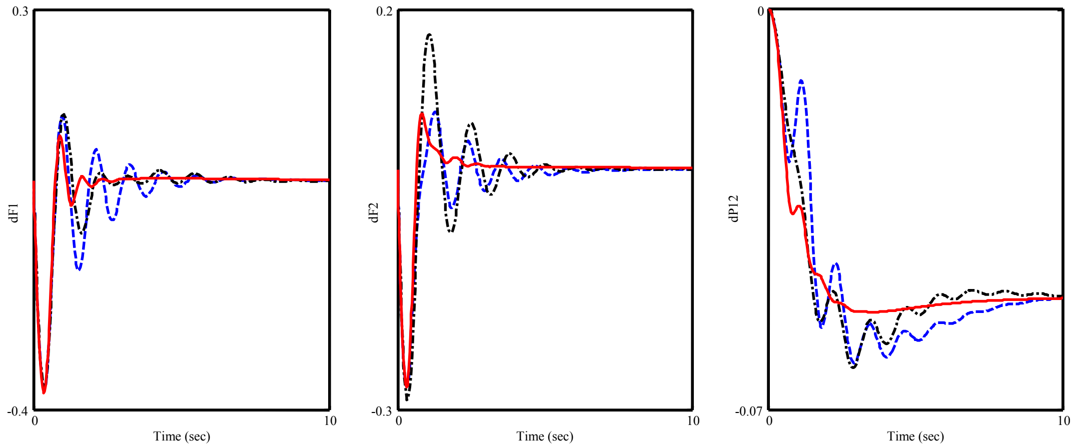

Figure 5. The performance of the controllers for scenario 1; Solid (ABC), Dashed (PSO), Dashed-dotted (GA)

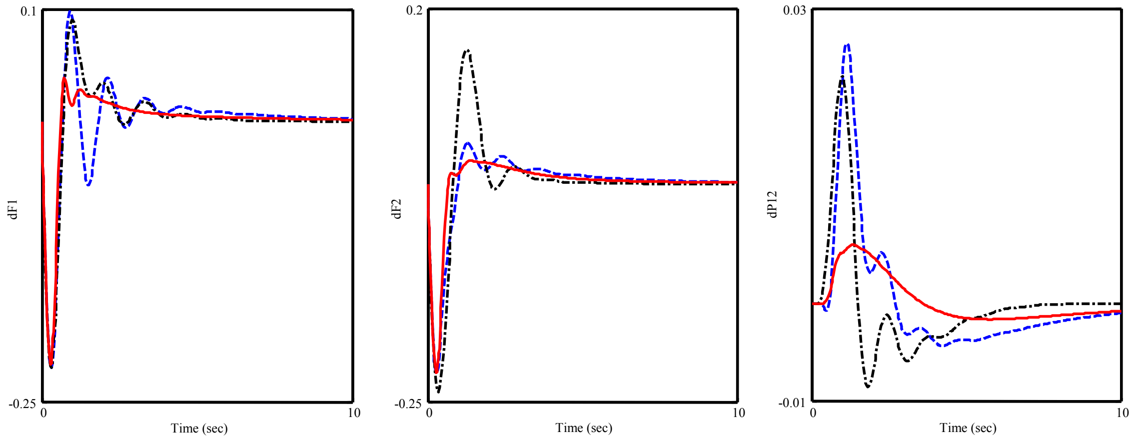

Figure 6. The performance of the controllers for scenario 2; Solid (ABC), Dashed (PSO), Dashed-dotted (GA)

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:

$$ITAE = 10\int_{0}^{10} t\,(|ACE_1(t)| + |ACE_2(t)|)dt \qquad (16)$$

$$FD = (OS \times 100)^2 + (US \times 20)^2 + T_s^2 \qquad (17)$$

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 under the two above scenarios, whereas the system parameters are varied from -25% to 25% of the nominal values. Table 2-3 show the values of *ITAE* and *FD* for different operation conditions with three control schemes. Examination of this Table reveals that the proposed control strategy achieves good robust performance against parametric uncertainties and system nonlinearities.

Remark 1: The worst case, as seen from all the simulation results, occurs when two areas are using upper bound parameters and having simultaneous load disturbances.

Remark 2: We have considered different cases for LFC control of a two-area power system. 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.

Table 2. Values of performance indices under scenario 1

Change of parameters	*ITAE*			*FD*		
	ABC	PSO	GA	ABC	PSO	GA
25%	0.3338	0.3378	0.5437	104.2637	158.3895	180.2471
20%	0.3185	0.3285	0.5281	104.7049	159.3092	182.7445
15%	0.3021	0.3225	0.5134	106.5553	162.1561	184.9889
10%	0.2854	0.3174	0.5001	107.5751	173.2985	187.8033
5%	0.2670	0.3125	0.4883	109.9003	179.1091	185.2052
nominal	0.2484	0.3075	0.4777	112.7625	183.9113	188.0024
-5%	0.2285	0.3022	0.4685	115.9133	190.1629	193.4161
-10%	0.2078	0.2971	0.4615	120.5255	195.4610	198.5217
-15%	0.1918	0.2921	0.4576	125.6920	203.2493	206.3624
-20%	0.1817	0.2887	0.4565	131.5804	224.7104	218.2846
-25%	0.1774	0.2942	0.4591	127.0223	237.2977	229.6354

Table 3. Values of performance indices under scenario 2

Change of parameters	*ITAE*			FD		
	ABC	PSO	GA	ABC	PSO	GA
25%	0.24	0.27	0.35	158.47	171.16	189.79
20%	0.22	0.26	0.33	151.81	176.0	192.81
15%	0.21	0.25	0.31	146.79	181.49	197.76
10%	0.19	0.24	0.28	144.44	187.81	202.28
5%	0.18	0.24	0.27	142.2	194.75	198.39
nominal	0.16	0.23	0.25	142.02	203.60	205.72
-5%	0.14	0.23	0.23	143.97	213.18	215.48
-10%	0.12	0.22	0.22	146.90	237.21	230.69
-15%	0.11	0.23	0.21	149.79	252.18	244.18
-20%	0.098	0.24	0.22	158.63	275.41	271.66
-25%	0.085	0.25	0.24	171.94	298.10	290.92

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 ABC algorithm has been successfully applied to the robust design of PID controllers for solution of the LFC problem in the restructured power system. 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 ABC technique which is a very simple, robust and population based stochastic optimization algorithm. Compared with the usual heuristic algorithms such as PSO, the major advantage of the ABC algorithm lays in that it conducts both global and local searches in each iteration, and as a result the probability of finding the optimal parameters is significantly increased, which efficiently avoid local optimum to a large extent.

The effectiveness of the proposed strategy was tested on a two-area restructured power system under possible contracts with various load changes in the presence of modeling uncertainties and GRC. The simulation results show that the proposed ABC based tuned PID controller achieves good robust performance for a wide range of system parameters and is superior to PSO and GA based tuned PID controllers. The system performance characteristics in terms of ‘ITAE’ and ‘FD’ 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 restructured power systems.

APPENDICES

Table 4. GENCOs parameters

MVA_{base} (1000 MW) Parameter	GENCOs (k in area i)			
	1-1	2-1	1-2	2-1
Rate (MW)	800	1000	1100	1200
T_T (Sec)	0.3	0.3	0.3	0.3
T_G (Sec)	0.08	0.08	0.08	0.08
R (Hz/p.u.)	2.4	2.4	2.4	2.4

Table 5. Control area parameters

Parameter	Area 1	Area 2
K_P (Hz/p.u.)	20	120
T_P (Sec)	20	120
B (p.u./Hz)	0.425	0.425
T_{12} (p.u./Hz)	0.545	

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