ABSTRACT: This paper presents the design and performance analysis of Artificial Bee Colony (ABC) algorithm based parallel 2-Degree Freedom of Proportional-Integral-Derivative (2-DOF-PID) controller for Load Frequency Control (LFC) of a two-area reheat thermal interconnected deregulated power system. The degree of freedom of a control system is defined as the number of closed-loop transfer functions that can be adjusted independently. The 2-DOF-PID controller produces an output signal based on the difference between a reference signal and a measured system output. It computes a weighted difference signal for each of the proportional, integral, and derivative actions according to the specified set point weights. The controller output is the sum of the proportional, integral, and derivative actions on the respective difference signals, where each action is weighted according to the chosen gain parameters. The advantages of 2-DOF-PID controller are used in a two area interconnected power system the overshoot can be suppressed almost completely without deteriorating the settling time. The proposed controller exhibits superior transient and steady-state performance compared to usual conventional Proportional-Integral (PI) controller. Moreover the ABC algorithm proposed in thesis is easy to implement without additional computational complexity. The advantage of this algorithm is ability to jump out the local optima, the convergence precision and speed are remarkably enhanced and thus the high precision and efficiency are achieved.

Key Words: 2-DOF-PID controller, Artificial Bee Colony, Load Frequency Control

I. INTRODUCTION

Load Frequency Control (LFC) is an important issue in electric power system design and operation for supplying sufficient and reliable electric power with good quality. The primary objectives of LFC are to regulate frequency to the specified nominal value and to maintain the interchange power between control areas at the scheduled values by adjusting the output of selected generator [1]. The main function of the LFC is to regulate a signal called Area Control Error (ACE), which accounts for error in the frequency as well as the errors in the interchange power with neighboring area [2]. Nowadays, the electric power industry is in transition to a competitive energy market. In the new structure, Gencos may not participate in the LFC task and Discos have the library to control with any available Gencos in their own or other areas. The goal of deregulation is to enhance competition and bring consumers new choices and economic benefits [3]. Several classical controllers structures such as Integral (I), Proportional-Integral (PI), Integral-Derivative (ID), Proportional-Integral-Derivative (PID) and Integral–Double Derivative (IDD) has been used in LFC [4]. It clear from literature survey that the performance of the system not only depends on the artificial intelligent techniques employed but also on controller structure and selection of objective function. Two-degree-of-freedom (2-DOF) controllers have an advantage over the classical single degree of freedom ones from the point of view of achieving high performance in set-point tracking and the regulation in the presence of disturbance inputs [5, 6]. Artificial Bee Colony (ABC) algorithm is a population-based direct search algorithm for global optimization capable of handling non-differentiable, non-linear and multi-modal objective functions, with few, easily chosen, control parameters [7]. ABC uses weighted differences between solution vectors to change the population, whereas in other stochastic techniques such as GA and Expert Systems (ES), perturbation occurs in accordance with a random quantity. ABC employs a greedy selection process with inherent elitist features. Also it has a minimum number of control parameters, which can be tuned effectively [8, 9]. In view of the above, an attempt has been made in this paper for the optimal design of ABC based 2-DOF-PID controller for LFC in two area reheat thermal interconnected power system. The design problem of the proposed controller is formulated as an optimization problem and ABC is employed to search for optimal controller parameters. Simulations results are presented to show the effectiveness of the proposed of parallel 2-Degree Freedom of Proportional-Integral-Derivative (2-DOF-PID) controller in
providing good damping characteristic to system oscillations over a wide range of loading conditions, and system parameters as compared to using PI controller.

II. DESIGN OF 2-DEGREE FREEDOM OF PID (2-DOF-PID) CONTROLLER

![Control structure of Two degree of freedom (2-DOP) PID controller](image)

The degree of freedom of a control system is defined as the number of closed-loop transfer functions that can be adjusted independently. The design of control systems is a multi-objective problem, so a two-degree-of-freedom (abbreviated as 2DOF) control system naturally has advantages over a one degree-of-freedom control system. The 2-DOF-PID controller produces an output signal based on the difference between a reference signal and a measured system output. It computes a weighted difference signal for each of the proportional, integral, and derivative actions according to the specified set point weights. The controller output is the sum of the proportional, integral, and derivative actions on the respective difference signals, where each action is weighted according to the chosen gain parameters [6].

![Two degree of freedom (2-DOP) PID control system](image)

The control structure of a Two degree of freedom (2-DOP) PID controller is shown in Fig 1, where \( R(s) \) \( K_P \), \( K_I \) and \( K_D \) are the proportional, integral and derivative gains respectively, \( PW \) and \( DW \) are the proportional and derivative set point weights respectively, and \( N \) is the derivative filter coefficient. For a parallel two-degree-of-freedom PID controller, \( C(s) \) is a single degree-of-freedom controller, \( D(s) \) is the load disturbance and \( F(s) \) acts as a pre filter on the reference signal. For a parallel two-degree-of-freedom PID controller, \( C(s) \) and \( F(s) \) are given by:

\[
F(s) = \frac{(PW K_P + DW K_D) s^2 + (PW K_P N + K_I) s + K_I N}{(K_P + K_D N) s^2 + (K_P N + K_I) s + K_I N} \tag{1}
\]

\[
C(s) = \frac{(K_P + K_D N) s^2 + (K_P N + K_I) s + K_I N}{s (s + N)} \tag{2}
\]
The Artificial Bee Colony (ABC) algorithm was introduced by Karaboga [8]. The algorithm mimics the food foraging behavior of swarms of honey bees. Honey bees use several mechanisms like waggle dance to optimally locate food sources and to search new ones. This makes them a good candidate for developing new intelligent search algorithms. It is very simple, robust and population based stochastic optimization algorithm. In ABC algorithm, the colony of artificial bees consists of three groups of bees: Employed bees (E_b), Onlookers (O_b) and Scout bees (S_b). Some of the bee of the colony consists of the employed artificial bees and the some includes the onlookers. For every food source, there is only one employed bee. In other words the number of employed bees is equal to the number of food sources around the hive. The employed bee who’s the food sources has been abandoned by the bees becomes a scout. In ABC algorithm the position of the food sources determines the solution and the amount of nectar represents to fitness of this respective solution. The foraging strategy is governed by three process namely initialization, Reproduction and Replacement of bee and selection.

a) Initialization
A randomly distributed initial populations solutions \([X_i=1, 2, 3...D]\) is being disspread over the \(D\) dimensional problem space

b) Reproduction
An artificial onlooker bee choose a food source depending on the probability value associated with that food source, \(P_i\), calculated by the following expression,

\[
P_i = \frac{f_i \cdot t_i}{\sum_{i=1}^{N} f_i \cdot t_i}
\]  

(4)

Where \(f_i\) the fitness values of the solution \(i\) which is proportional to the nectar amount of the food source in the position \(i\) and \(N\) is the number of food sources which is equal to the number of employed bees. In order to produce a candidate food position from the old one in memory, the ABC uses the following expression,

\[
V_{ij} = x_{ij} + \Psi_{ij} (x_{ij} - x_{kj})
\]

(5)

Where \(k = (1,2,3,...D)\) and \(j = (1,2,3...N)\) are randomly chosen indexes \(\Psi_{ij}\) is a random number between [-1, 1].

c) Replacement of Bee selection
In ABC, providing that a position cannot be improved further through a predetermined number of cycles, then that food source is assumed to be abandoned. The value of pre determined number of cycles is an important control parameter of the ABC algorithm, which is called “limit” for abandonment. Assume that the abandoned source is \(X_i\) and \(j = (1,2,3,...N)\), then the scout discovers a new food source to be replaced with \(X_i\). This operation can be defined as

\[
X_{ij} = X_{\text{min}} + \text{rand}(0,1)*\left(X_{\text{max}} - X_{\text{min}}\right)
\]

(6)

After each candidate source position \(V_{ij}\) is produced and then evaluated by the artificial bee, its performance is compared with that of its old one. If the new food has equal or better nectar than the old source, it replaces the old one in the memory. Otherwise, the old one is retained in the memory.

$$J = \int_0^T \{(\beta_1 \Delta f_1)^2 + (\beta_2 \Delta f_2)^2 + (\Delta P_{\text{tie}})^2\}$$

(3)

III. ABC ALGORITHM FOR THE DESIGN OF 2-DOF-PID CONTROLLER

The Artificial Bee Colony (ABC) algorithm was introduced by Karaboga [8]. The algorithm mimics the food foraging behavior of swarms of honey bees. Honey bees use several mechanisms like waggle dance to optimally locate food sources and to search new ones. This makes them a good candidate for developing new intelligent search algorithms. It is very simple, robust and population based stochastic optimization algorithm. In ABC algorithm, the colony of artificial bees consists of three groups of bees: Employed bees (\(E_b\)), Onlookers (\(O_b\)) and Scout bees (\(S_b\)). Some of the bee of the colony consists of the employed artificial bees and the some includes the onlookers. For every food source, there is only one employed bee. In other words the number of employed bees is equal to the number of food sources around the hive. The employed bee who’s the food sources has been abandoned by the bees becomes a scout. In ABC algorithm the position of the food sources determines the solution and the amount of nectar represents to fitness of this respective solution. The foraging strategy is governed by three process namely initialization, Reproduction and Replacement of bee and selection.

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IV. MODELING OF TWO-AREA THERMAL REHEAT POWER SYSTEM IN DEREGULATED ENVIRONMENT

In the deregulated power system, Discos in every area can bond with Gencos in its own or other areas. There are several Gencos and Discos in the deregulated power system and a Disco has the liberty to have a contract with any Genco for contract of power. Such transactions are called bilateral transactions [3]. All the transactions have to be cleared through an impartial entity called an ICA. In this study two-area thermal reheat deregulated power system is considered in which each area has two Gencos and two Discos is shown in Fig 3. In the new environment, Discos may contract power from any Gencos and ICA has to supervise these contracts. DPM is a matrix in which the number of rows is equal to the number of Gencos and the number of columns is equal to the number of Discos in the system. Each entry in this matrix can be considered for the portion of a total load contracted by a Disco towards a Genco. The sum of all the entries in a column DPM is unity. From the Fig 3, Let Genco$_1$, Genco$_2$, Disco$_1$, Disco$_2$ be in area 1 and Genco$_3$, Genco$_4$, Disco$_3$, Disco$_4$ be in area 2. The corresponding DPM is given as follows

$$DPM = \begin{bmatrix} \text{cpf}_{11} & \text{cpf}_{12} & \text{cpf}_{13} & \text{cpf}_{14} \\ \text{cpf}_{21} & \text{cpf}_{22} & \text{cpf}_{23} & \text{cpf}_{24} \\ \text{cpf}_{31} & \text{cpf}_{32} & \text{cpf}_{33} & \text{cpf}_{34} \\ \text{cpf}_{41} & \text{cpf}_{42} & \text{cpf}_{43} & \text{cpf}_{44} \end{bmatrix}$$

Fig 3: Transfer function model of two area thermal-thermal power system in deregulated environment
where \( cpf \) represents "contract participation factor" i.e. p.u. MW load of a corresponding Disco. The scheduled steady state power flow on the tie-line is given by [3]

\[
\Delta P_{\text{Scheduled}}^{\text{Tie}12} = \sum_{i=1}^{2} \sum_{j=1}^{4} cpf_{ij} \Delta P_{Lj} - \sum_{i=1}^{4} \sum_{j=1}^{2} cpf_{ij} \Delta P_{Lj}
\]

(8)

The actual tie-line power is given as

\[
\Delta P_{\text{Actual}}^{\text{Tie}12} = \frac{\Delta F_{1} - \Delta F_{2}}{s}
\]

(9)

At any given time, the tie-line power error is given by [3]

\[
\Delta P_{\text{Error}}^{\text{Tie}12} = \Delta P_{\text{Actual}}^{\text{Tie}12} - \Delta P_{\text{Scheduled}}^{\text{Tie}12}
\]

(10)

\( \Delta P_{\text{Error}}^{\text{Tie}12} \) vanishes in the steady as the actual tie-line power flow reaches the scheduled power flow. This error signal is used to generate the respective Area Control Error (ACE) signals as in the traditional scenario [9].

\[
ACE_{1} = \beta_{1} \Delta F_{1} + \Delta P_{\text{Error}}^{\text{Tie}12}
\]

(11)

\[
ACE_{2} = \beta_{2} \Delta F_{2} + a_{12} \Delta P_{\text{Error}}^{\text{Tie}12}
\]

(12)

The generation of each Genco must footpath the contracted demands of Discos in steady state.

The desire total power generation of \( i^{th} \) Genco in terms of DPM entries can be calculated as

\[
\Delta P_{mi} = \sum_{i=1}^{4} cpf_{ij} \Delta P_{Lj}
\]

(13)

As there are two Gencos in each area, ACE signal has to be dispersed among them in proportion to their participation in the AGC. Coefficients that distribute ACE to Gencos are termed as "ACE Participation Factors (apfs)". In a given control area, the sum of participation factors is equal to 1. Hence, \( apf_{11}, apf_{12} \) are considered as ACE participation factor in area 1 and \( apf_{21}, apf_{22} \) are in area 2.

### V. SIMULATION RESULTS AND OBSERVATIONS

Artificial Bee Colony Algorithm based 2-DOF-PID controller are designed and implemented for LFC application in a two-area interconnected thermal reheat power system in deregulated environment. The gains of 2-DOF-PID controller are optimized using ABC algorithm by using off-line gain scheduling control method. The results are obtained by MATLAB software run on the computer which includes Core2 of 2 GHz, and RAM of 1 GB. The number of iteration and the population size are taken 50 and 100 respectively. The relevant parameters are given in Appendix. To satisfy the above requirement of LFC loop, the minimum and maximum values of PID controller parameters are chosen as 0 and 1.0. The set points weights PW and DW control the control action when a reference change takes place and lie in the range of 5. The derivative filter time constant N is generally a value greater than one. In this study, the ranges of PW, DW and N are taken as 1.0, 5, and 100 respectively. The performance of 2-DOF-PID controller are analyze for the test systems under Poolco based transactions and bilateral transactions as compared with PI controller.

**Scenario 1: Poolco based transaction**

In this scenario, Gencos participate only in the load following control of their areas. It is assumed that a large step load 0.15 pu MW is demanded by each Disco in area 1. Assume that a case of Poolco based contracts between Discos and available Gencos is simulated based on the following Disco Participation Matrix (DPM) referring to Eq (7) is considered as

\[
DPM_{1} = \begin{bmatrix}
0.5 & 0.5 & 0.0 & 0.0 \\
0.5 & 0.5 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 \\
\end{bmatrix}
\]

(14)

Disco1 and Disco2 demand identically from their local Gencos, viz., Genco1 and Genco2. Therefore, \( cpf_{11} = cpf_{12} = 0.5 \) and \( cpf_{21} = cpf_{22} = 0.5 \). The optimum control parameters of PI and 2-DOF-PID controllers are shown in Table 1 and the comparative system dynamic response of all controllers is shown in Fig 4. The peak over/under shoot and settling time of frequency deviation of both areas and tie-line power deviation with different controller are tabulated in Table 2. From the Table 2 and the Fig 4, it can be observed that the proposed 2-DOF-PID controller have better dynamic responses as compared with PI controller in terms of peak over/undershoot and settling time of frequency deviation both areas and tie-line power oscillations in LFC loop.

**Scenario 2: Bilateral based transactions**

Here all the Discos have contract with the Gencos and the following Disco Participation Matrix (DPM) referring to Eq (7) is considered as
In this case, the Disco1, Disco2, Disco3 and Disco4 demands of 0.1 pu.MW for each from Gencos as defined by cpf in the DPM matrix and each Gencos participates in AGC as defined by the following ACE participation factor apf_{11} = apf_{12} = 0.5 and apf_{21} = apf_{22} = 0.5. The optimal values of corresponding controller’s parameters are tabulated in Table 1 the corresponding results are tabulated in Table 2. From the results show that 2-DOF-PID controller is performing improved in comparison to PI controllers because of smaller peak variations and time to settle. The main merit of 2-DOF-PID controller has good stability for different transactions, excellent transient and dynamic responses in comparison with PI controllers.

Table 1 optimum values of control parameters of different controllers under Poolco and Bilateral based transactions

<table>
<thead>
<tr>
<th>controller</th>
<th>Gain/parameters</th>
<th>Poolco based transactions</th>
<th>Bilateral based transactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>K_{Pl}</td>
<td>0.3423</td>
<td>0.2687</td>
</tr>
<tr>
<td></td>
<td>K_{Ii}</td>
<td>0.3978</td>
<td>0.3478</td>
</tr>
<tr>
<td>2-DOF-PID</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>K_{Pl}</td>
<td>0.5487</td>
<td>0.5487</td>
</tr>
<tr>
<td></td>
<td>K_{Ii}</td>
<td>0.6458</td>
<td>0.6472</td>
</tr>
<tr>
<td></td>
<td>K_{Dii}</td>
<td>0.8752</td>
<td>0.7158</td>
</tr>
</tbody>
</table>

Table 2 Comparative dynamic responses for different controller under Poolco and Bilateral based transactions

<table>
<thead>
<tr>
<th>Transactions</th>
<th>controller</th>
<th>Peak overshoot</th>
<th>Peak undershoot</th>
<th>Setting time in sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poolco</td>
<td>PI</td>
<td>0.101</td>
<td>0.005</td>
<td>0.453</td>
</tr>
<tr>
<td></td>
<td>2-DOF-PID</td>
<td>0.061</td>
<td>0.003</td>
<td>0.353</td>
</tr>
<tr>
<td>Bilateral</td>
<td>PI</td>
<td>0.123</td>
<td>0.000</td>
<td>0.347</td>
</tr>
<tr>
<td></td>
<td>2-DOF-PID</td>
<td>0.084</td>
<td>0.002</td>
<td>0.214</td>
</tr>
</tbody>
</table>
VI. CONCLUSION
Artificial Bee Colony algorithm based a parallel 2-DOF-PID controller for Load Frequency Control of two-area thermal reheat power systems is presented in this paper. The control parameters of 2-DOF PID controller are optimized through ABC algorithm. The ABC algorithm proposed in paper is easy to implement without additional computational complexity. While designing a control system various performance criteria are to be satisfied so a two-degree-of-freedom control system naturally has advantages over the conventional single degree of freedom control system. The 2-DOF controller produces an output signal based on the difference between a reference signal and a measured system output. It computes a weighted difference signal for each of the proportional, integral, and derivative actions according to the specified set point weights. The controller output is the sum of the proportional, integral, and derivative actions on the respective difference signals, where each action is weighted according to the chosen gain parameters. The conventional PI control system is tuned to optimize the disturbance response; the set-point response tends to have a large overshoot. To overcome this drawback, the 2-DOF-PID controller are used in a two area interconnected power system and the overshoot can be suppressed almost completely without deteriorating the settling time. From these simulation results, it can be observed that the oscillations in area frequencies and tie-line power deviation have decreases to a considerable extent using parallel 2-DOF-PID controller as compare to that of the system using PI conventional controller.

VII. ACKNOWLEDGEMENT
The authors wish to thank the authorities of Annamalai University, Annamalainagar, Tamilnadu, India for the facilities provided to prepare this paper.
REFERENCES


APPENDIX –A

Data for the interconnected two- area thermal Reheat Power System [15]

Rating of each area = 2000 MW, Base power = 2000 MVA, f = 60 Hz, R1 = R2 = R3 = R4 = 2.4 Hz / p.u.MW, Tg1 = Tg2 = Tg3 = Tg4 = 0.08 s, T11 = T12 = T13 = T14 = 10 s, T11 = T12 = T13 = T14 = 0.3 s, Kp1 = Kp2 = 120Hz/p.u.MW, Tp1 = Tp2 = 20 s, \( \beta_1 = \beta_2 = 0.425 \) p.u.MW / Hz, K1 = K2 = K3 = K4 = 0.5, \( 2\pi T_12 = 0.545 \) p.u.MW / Hz, a12 = -1.