Optimal Fractional Order PID Controller for Centralized and Decentralized Frequency Control in Restructured Power System

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Abstract: In this research paper, an attempt has been made to design a Fractional order PID (FOPID) controller employed for centralized and decentralized frequency control in a restructured power system. The controller gains are optimized by Moth Flame Optimization algorithm (MFO), with Integral Time Absolute Error (ITAE) as objective function. The performance of the FOPID controller is compared with that of conventional PID controller under various contract scenarios. It is observed that FOPID as a frequency error damping controller, the steady state and dynamic performance of the proposed power system is enhanced.

Index Terms: Automatic Generation Control, Bilateral Contracts, Fractional Order Controller, Regulation.

I. INTRODUCTION

Power system control is one of the most critical and essential functions in a power market as both active and reactive power requirements are never constant and are increasing or decreasing continuously. The deviations in the frequency must be eliminated by balancing active power generation with the load through a proper control mechanism. In restructured power structure, the centralized frequency correction service is termed as Regulation or Automatic Generation Control (AGC) and the decentralized frequency regulatory service is known as Load Following (LF). Among the various control strategies, AGC [1] is the basic control structure in the power system operation. The various problems of load frequency control after deregulation have been reviewed in detail [2-6]. The major approaches used for frequency control which focus on designing proportional-integral-derivative (PID) controller [7], contemporary control approaches [8-12]. Intelligent control schemes such as neural networks [13-14] fuzzy logic-based control [15] and Soft computing-based approaches for controller parameter tuning are found in the literature. In most of the literature, PID controller has been used for eliminating the frequency error. Over the past few years, a increasing interest has been shown in fractional order controller, which has inspired many issues in the fields of automation, robotics, energy systems, etc. to be solved efficiently. The authors in [16-17] have applied fractional-order proportional–integral–derivative controller (FOPID) for automatic generation control (AGC). The authors in [18] have analyzed “deregulated AGC Multi area system using FOPI and FOPID cascaded controller with geothermal, solar and thermal power plants”. Rajesh [19] has applied load following controller for AGC in restructured power system. For frequency regulation in conventional power system as well as restructured power system, mostly the traditional PID controller has been used. Even though, the PID controller exhibits good dynamic performance characteristics, alternate controllers like FOPID are applied for frequency control in conventional vertically integrated utilities and restructured power structure as well. Also, PID controller has only three gains $K_p, K_i$ and $K_d$ as tuning parameters, whereas FOPID controller has five tuning parameters, $K_p, K_i, K_d, \lambda$ and $\mu$. The additional two degree of freedom makes the FOPID more adaptable and robust.

According to the optimization theorem of No-Free-Lunch (NFL) [20], not all algorithms can solve all the issues of optimization. Fractional order systems are based on fractional order calculus [21-22] which, with few coefficients, can represent dynamic systems with high order dynamics and complicated nonlinear phenomena. The dynamics of the integer-order portray the particular and lower class of fractional-order systems. Thus, as established by many researchers, such as [23-24], fractional-order controllers surpassed their counterparts in the integer-order. The author in [25], proposed MFO, a nature inspired optimization algorithm. In recent years, MFO algorithm has been found effective for many of the power system optimization problems [27-30]. Even though there are many population-based algorithms available for optimization, MFO has been chosen in our present work because of its simplicity does not need any information about the system, (i.e.) the mathematical background of the proposed system. Being a population-based algorithm, local optima is avoided which makes it suitable for practical applications. MFO can also handle constrained and unconstrained problems.
MFO depends much on problem representation than the nature and structure of the problem. Therefore, it can be readily used for any type of optimization problem. It is observed in the literature that, MFO is highly efficient in achieving the global optimum, and is also efficient in balancing search space exploration and exploitation. Due to the adaptive convergence characteristic, MFO has very good convergence speed. Hence in our present work MFO is selected as an optimizer for minimizing the frequency error. 

In the literature, the performance index Integral Time Absolute Error(ITAE) is widely used for optimization. ITAE criteria gives integration of time multiplied by Absolute Error and weightage is given to those which exist over a longer time than those at the initial stage. The reduction in settling time is achieved by allocating larger multiplication factor to the error at final stages rather than the initial ones. The objectives of the present article are:(i)To Simulate the centralized and decentralized control strategy in a two-area restructured power system using PID and FOPID controller with bilateral contract structure under for different cases.(ii) To obtain the optimal controller gains using MFO algorithm by employing ITAE as objective function. And (iii) To prove the effectiveness of FOPID controller over PID via qualitative and quantitative analysis of results. To prove the effectiveness of the FOPID controller and MFO algorithm, the system given in [19] is taken for simulation. 

II. SYSTEM UNDER STUDY

A. Components of the proposed system

In the proposed system [19], there are two control areas in which each area has two GCs and two DCs respectively. Both the GCs are having non-reheat thermal units and the DCs which have the liberty of any GC to contract. Any DC in region1 may contract separately through bilateral transactions with any GC in another control region, say Area-2. The Disco Participation Matrix (DPM) shows the different Contract Participation Factors (fcp) agreements that occur between GCs and DCs.

![Fig. 1 Structure of two-area interconnected power system in competitive market](image)

The diagonal blocks of the DPM given by equation.4 corresponds to local demands i.e the demands of DCs in an area from the GCs in the same area. The demand of the DCs in one area from the GCs in another area is represented by the off-diagonal blocks.

Fig.1 illustrates the competitive two area power system. The two-area interconnected system transfer function model is shown in Fig.2. The notations used in the block diagram are explained in Appendix I. As shown in Fig.2, in the two-area interconnected system, the governor, turbine and the power system are represented by their equivalent transfer function models. In each area there is an AGC controller to distribute the ACE errors to the areas.

![Fig. 2 Decentralized and Centralized frequency control scheme for two area restructured power system][19](image)

This functions as a primary control mechanism to bring to zero the deviations in frequency and tie line power. Each generating unit is supported by a load following controller locally which helps the generation units to supply the power contracted by the loads. The ACE signal is given as input to the AGC controller. For the load following controller, Generation Control Error (GCE) is given as input signal. Parameters of the framework used for simulation are given in Appendix II.

The heat units used in each region have a 10 percent GRC (Generation Rate Constraint), as shown in Figure 3.
Bilateral contract between a GC and a DC can be related by DC participation Matrix known as DPM. As the proposed system has NG = 4 and ND = 4, the DPM will be of the order of 4 x 4.

\[
DPM = \begin{bmatrix}
fcp_{p1} & fcp_{p2} & fcp_{p3} & fcp_{p4} \\
fcp_{p21} & fcp_{p22} & fcp_{p23} & fcp_{p24} \\
fcp_{p31} & fcp_{p32} & fcp_{p33} & fcp_{p34} \\
fcp_{p41} & fcp_{p42} & fcp_{p43} & fcp_{p44}
\end{bmatrix}
\]

(1)

The GCs and DCs are represented by the rows and columns of the DPM matrix respectively. The fcp is the ratio of the power demanded from \( m \)th GC to the total demand of \( n \)th DC. In this matrix, the sum of all the entries in a column is unity. The contracted power of GCs with DCs is given by

\[
\Delta P_{gcm} = \sum_{i=1}^{NDC} cpf_{mi} \Delta P_{Ln}
\]

(2)

where \( \Delta P_{gcm} \) is the contracted power of \( m \)th generating unit, \( \Delta P_{Ln} \) total demand of \( n \)th DC and \( cpf_{mi} \) contract participation factor between \( n \)th DC and \( m \)th GC. The scheduled steady state power flow on the tie-line is given as,

\[
\Delta P_{tie12, sch} = (Demand \ of \ DCs \ in \ area-2 \ from \ GCs \ in \ area-1) - (Demand \ of \ DCs \ in \ area-1 \ from \ GCs \ in \ area-2)
\]

(3)

The scheduled power flow on the tie-line at steady state is calculated as,

\[
\Delta P_{tie12, sch} = \sum_{m=1}^{4} \sum_{n=1}^{4} cpf_{mn} \Delta P_{Ln} - \sum_{m=1}^{4} \sum_{n=4}^{4} cpf_{mn} \Delta P_{Ln}
\]

(4)

The tie-line power error, \( \Delta P_{tie12, err} \) is the difference between the actual power flow and the scheduled power flow.

The actual tie-line power flow is equal to the scheduled power flow at steady state. Hence, tie-line power error, \( \Delta P_{tie12, err} \) reduces to zero. The ACE signals are generated using this error signal.

\[
ACE_i = B_i \Delta F_i + \Delta P_{tie12, err}
\]

(5)

The contracted power of DCs are illustrated in Fig.4.

In each area two types control actions take place. The first one is Frequency Regulation or AGC which is the centralized control. AGC controller is fed with ACE as input signal. The other one is Load Following (LF) action which is a decentralized control. As seen from the above figure, the contracted load signal \( \Delta P_{gcm} \) originates from a \( n \)th DC is compared with the generated output signal of \( m \)th GC, \( \Delta P_{gm} \). This is applicable while \( m \)th GC and \( n \)th DC are in contract. The difference between \( \Delta P_{gcm} \) and \( \Delta P_{gm} \) is known as Generation Control Error (GCE). This is given as input command signal to the LF units. The LF controller reduces GCE by following the load. By minimizing this error, the generating units are made to supply the contracted power to the loads.

GCE for the load following units are given by Eqn. (6)

\[
GCE_m = \Delta P_{gcm} - \Delta P_{gm}
\]

(6)

\( \Delta P_{L1, LC} \) is the sum of contracted power demanded by DC1 and DC2. Similarly, \( \Delta P_{L2, LC} \) is the sum of contracted power demanded by DC3 and DC4. The noncontracted demands of DCs are \( \Delta P_{UC1} \), \( \Delta P_{UC2} \), \( \Delta P_{UC3} \) and \( \Delta P_{UC4} \). The distribution of noncontracted power is resolved by the ACE Participation Factors (fcp) among various GCs in each area at steady state. It is important to note that the apfs, \( A_1 + A_2 = 1.0 \) in Area -1 and \( A_3 + A_4 = 1.0 \) in Area-2.

Fig. 4 Contracted power of DCs in competitive ancillary service market

B. Case Description

The three different cases simulated along with bilateral contracts are explained in Table.1.
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Table 1: Description of control scenarios

| Case No | AGC | Load following | Contract Violation |
|---------|-----|----------------|-------------------|
|         | Area 1 | Area 2 | GC 1 | GC 2 | GC 3 | GC 4 |
| Case 1  | No     | No     | No   | Yes  | No   | Yes  | No   |
| Case 2  | Yes    | Yes    | No   | Yes  | No   | Yes  | No   |
| Case 3  | Yes    | Yes    | No   | Yes  | No   | Yes  | Yes  |

Case 1: Only load following, No contract violation

It is assumed that no GC participates in AGC and there is no contract violation. In Area-1, GC1 is for speed regulation and GC2 is for load following. Also, in Area-2, GC3 is for speed regulation and GC4 is for load following. Since there is no AGC, no centralized controller is available. All the DCs are assumed to have a load of 0.005 puMW each. The contracts between the GCs and DCs in both the areas are described in DPM given in Eqn. (7).

$$DPM = \begin{bmatrix}
0 & 0 & 0 & 0 \\
0.25 & 0.10 & 0.75 & 0.60 \\
0 & 0 & 0 & 0 \\
0.75 & 0.90 & 0.25 & 0.40 
\end{bmatrix}$$

(7)

Also, it is assumed that there is no contract violation. It is assumed that all the four DCs possess a load demand of 0.005 puMW which is contracted to the available GCs as per the DPM given above. Hence $\Delta P_{g1,s} = \Delta P_{g2,s} = \Delta P_{g3,s} = \Delta P_{g4,s} = 0.005$ puMW. Therefore, the contracted local load for Area-1 is 0.01pu MW and for Area-2 is 0.01pu MW. At steady state the generating unit generates power equal to the power contracted by the respective unit given by,

$$\Delta P_{gm,s} = \Delta P_{gm}$$

(8)

It is calculated for each GC using the DPM given above using equations (2) and (8) and given in Table 2. The steady state outputs of the Gencos in Area 1 & 2 are calculated using the DPM given in Eqn. (7). The tie-line power scheduled is calculated using Eqn. (4) is -0.0015 p.uMW.

Case 2: Both AGC and load following

Table 2 illustrates the distribution of contracted power from the Gencos to the respective Discos. The GC1 and GC3 are under AGC. The DPM is same as in Case 1. The ACE participation factors for the GC1 and GC3 are 1. GC2 and GC4 are under LF. Therefore, ACE participation factors for GC 2 and GC 4 are zero. It is also assumed that there is no non contracted demand in any of the areas. The DCs have 0.005 puMW of contracted demand which is to be met by the GC2 and GC4 since these two participate in load following. The GCs outputs at steady state are same as Case 1. The steady state generated outputs of the four Gencos are same as in Case 1, and the values are given in Table 3. The tie-line power scheduled is calculated using Eqn. (5) is -0.0015 p.uMW, same as in Case 1 since there is no contract violation.

Table 2: Steady state output of Gencos – Case 1 and Case 2

| Genco | Steady State output in puMW |
|-------|-----------------------------|
| $\Delta P_{g1,ss}$ | $(0+0+0+0) \times 0.005 = 0$ |
| $\Delta P_{g2,ss}$ | $(0.25 +0.1+ 0.75 + 0.60) \times 0.005 = 0.0085$ |
| $\Delta P_{g3,ss}$ | $(0+0+0+0) \times 0.005 = 0$ |
| $\Delta P_{g4,ss}$ | $(0.75 + 0.9 + 0.25 + 0.4) \times 0.005 = 0.0115$ |

Case 3: Both AGC and load following with contract violation

In this case, an uncontracted load demand of 0.005 puMW is introduced in Area-1. The contracted demand, DPM and APFs are same as in Case 2. This uncontracted demand along with the contracted demand of 0.005 puMW will introduce error in Area-1 ACE. This can be nullified by additional generation by the GCs in Area-1. As there are two GCs in Area-1, this uncontracted demand will be shared among the two GCs. The amount of sharing depends on the value of APFs. In the presence of uncontracted demand, the steady state power output of the GCs gets modified according to Eqn. (9).

$$\begin{bmatrix}
\Delta P_{g1,ss} \\
\Delta P_{g2,ss} \\
\Delta P_{g3,ss} \\
\Delta P_{g4,ss}
\end{bmatrix} = \begin{bmatrix}
A_1 & 0.0 & 0.0 & 0.0 \\
0.0 & A_2 & 0.0 & 0.0 \\
0.0 & 0.0 & A_3 & 0.0 \\
0.0 & 0.0 & 0.0 & A_4
\end{bmatrix} \begin{bmatrix}
\Delta P_{L1,UC} \\
\Delta P_{L2,UC} \\
\Delta P_{L3,UC} \\
\Delta P_{L4,UC}
\end{bmatrix} + \begin{bmatrix}
\Delta P_{g1} \\
\Delta P_{g2} \\
\Delta P_{g3} \\
\Delta P_{g4}
\end{bmatrix}$$

(9)

The GC1 sharing of apf is 1 i.e., $A_1$ = 1 and of GC2 i.e $A_2 = 0$. Hence the additional generation will be favored by GC1 in Area-1.

Table 3: GENCos output power as per Disco demands for Case 1 and Case 2

| Area-1 | Area-2 | Total (puMW) |
|--------|--------|--------------|
| DC1    | DC2    | DC3          | DC4          |
| Case 1 |        |              |              |
| GC1    | 0      | 0            | 0            | 0            |
| GC2    | 0.001  | 0.0005       | 0.003        | 0.008        |
|        | 25     | 75           | 3            | 5            |
| GC3    | 0      | 0            | 0            | 0            |
Table 4: Steady state output of Gencos – Case 3

| Genco | Components of Contract violation | Steady State output in puMW |
|-------|----------------------------------|-----------------------------|
| GC1   | \( (A_1 \times \Delta P_{g_{1,U}}) + \Delta P_{g_{1}} \) | \((1 \times 0.005) + 0 = 0.005\) |
| GC2   | \( (A_2 \times \Delta P_{g_{2,U}}) + \Delta P_{g_{2}} \) | \((0 \times 0.005) + 0.0085 = 0.0085\) |
| GC3   | \( (A_3 \times \Delta P_{g_{3,U}}) + \Delta P_{g_{3}} \) | \((1 \times 0) + 0 = 0\) |
| GC4   | \( (A_4 \times \Delta P_{g_{4,U}}) + \Delta P_{g_{4}} \) | \((0 \times 0) + 0.0115 = 0.0115\) |

The steady output of GCs in Area-1 and Area-2 during contract violation is calculated and given in Table 4. It is worthwhile to note that the power output of GC2 is 0 since \( A_2 = 0 \). Similarly in Area-2, \( A_3 = 1 \) since there is no contract violation, the GC2 output remains same as in Case 2. Also \( A_4 = 0 \) which eventually result in the same power output of 0.0115 puMW. \( \Delta P_{g_{1,U}} \) and \( \Delta P_{g_{2,U}} \) are taken as 0.005 puMW and the steady state output of the four Gencos are calculated using Eqn. (9), as follows:

\[ \Delta P_{tie, sch} = -0.0015 \text{puMW}. \]

The noncontracted load demand of 0.005 puMW in Area -1 is met by the generating unit under AGC i.e. GC1, while the generation of the other Genco i.e. GC2 in area 1 at steady state is same as previous case.

III. CONTROLLER AND OPTIMIZATION

A. FOPID controller

Fractional calculus is a generalization of the traditional integer-order calculus which encompasses fractional-order integro-differential operators. The transfer function of PI\(^D\)\(^\lambda\), the FOPID controller is given by

\[ G_c(s) = K_p + \frac{K_i}{s^\lambda} + K_d s^\mu \quad (10) \]

There are five parameters \( (K_p, K_i, K_d, \lambda, \mu) \) that have to be tuned, this improves the flexibility to meet pre-set design demands such as static errors, phase and gain margins, and robustness. The challenge of this work is to create a feasible FOPID controller that achieves the design demands by exhibiting solid efficiency. The main point is to seek acceptable differential operators’ approximations \( \lambda \) and \( s^\mu \).

The block diagram of FOPID controller is shown in Fig. 5.

B. Objective function

ITAE is used as an objective function for FOPID controller gain tuning through optimization.

\[ J = ITAE = \int_0^{\infty} |\Delta F_1| + |\Delta F_2| + |\Delta P_{tie}| t \, dt \quad (11) \]

where \( \Delta F_1 \) and \( \Delta F_2 \) are the system frequency deviation in area-1 and area-2 respectively. \( \Delta P_{tie} \) is the incremental change in tie-line power and \( t \) is the time interval of simulation. The boundaries on controller gains are the constraints. The design problem can, therefore, be formulated as,

Minimize \( J \), subjected to

\[ K_{PL} \leq K_p \leq K_{PU} \quad (12a) \]
\[ K_{IL} \leq K_i \leq K_{IU} \quad (12b) \]
\[ K_{DL} \leq K_d \leq K_{DU} \quad (12c) \]
\[ \hat{\lambda} \leq \lambda \leq \hat{\lambda} \quad (12d) \]
\[ \hat{\mu} \leq \mu \leq \hat{\mu} \quad (12e) \]

where \( J \) is the objective function denoted in (11) and the minimum and maximum bounds for the controller gains and the fractional operators are given in Eqns.12.a -12.e.

C. MFO Algorithm [25]

MFO algorithm exploits moths' navigation behavior during night time. Moths use transverse orientation mechanism to fly at night using the moon. Moths have a unique technique of travelling in a straight line maintaining their respective distance with the moon light as flame. This technique is incorporated in the algorithm taking moths as search agents and the flame as the solution set. The solution set is updated with the position of each moth and the better position is stored.
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The initial population of moths is randomly generated and the evaluation criterion compares the best moths to that of the best flames, which corresponds to the best optimal values. Flames are often updated by the moths which make sure that the moths never lose best solutions and are retained as flags. The flame matrix, moth matrix, spiral motion of moth is all considered as parameters changing in each iteration. The optimization problem is assumed to be of \( d \)-dimension with \( n \)-decision variables in the search space with desired values. The search space consists a population of \( n \)-moths as search agents in which each moth has a \( d \)-dimensional vector as the candidate solution to the issue. In \( d \)-dimensional space, the moths are flying and their positions are the potential solutions. The following \( n \times d \) matrix describes the collection of moths and their positions.

\[
M = \begin{bmatrix}
M_{11} & M_{12} & \ldots & M_{1d} \\
M_{21} & M_{22} & \ldots & M_{2d} \\
\vdots & \vdots & \ddots & \vdots \\
M_{n1} & M_{n2} & \ldots & M_{nd}
\end{bmatrix}
\]  \hfill (13)

The vector \( OM \) stores the fitness values as:

\[
OM = \begin{bmatrix}
OM_1 \\
OM_2 \\
\vdots \\
OM_n
\end{bmatrix}
\]  \hfill (14)

The flames are represented by the following matrix

\[
F = \begin{bmatrix}
F_{11} & F_{12} & \ldots & F_{1d} \\
F_{21} & F_{22} & \ldots & F_{2d} \\
\vdots & \vdots & \ddots & \vdots \\
F_{n1} & F_{n2} & \ldots & F_{nd}
\end{bmatrix}
\]  \hfill (15)

The fitness values of flames are stored in a vector given as:

\[
OF = \begin{bmatrix}
OF_1 \\
OF_2 \\
\vdots \\
OF_n
\end{bmatrix}
\]  \hfill (16)

From mathematical point of view, MFO has three components:

\[
MFO = (I, P, T)
\]  \hfill (17)

where \( I \) is the function which generates a random population of moths and corresponding fitness values, \( P \) is the update function and \( T \) is the termination function.

The upper and lower bound decision variables \( ub \) and \( lb \) are two vectors which are represented as follows:

\[
ub = [ub_1, ub_2, \ldots, ub_d]
\]  \hfill (18)

\[
lb = [lb_1, lb_2, \ldots, lb_d]
\]  \hfill (19)

The iteration can be initiated once the function \( I \) produces the original solution and the function \( P \) runs in iterations until the termination is announced by the function \( T \). The update feature, \( P \) is the primary component of the MFO moving moths around the search space and updating the flames position. The MFO algorithm flow chart is shown in Fig.6.

D. Implementation

For the proposed system, FOPID controller is applied for the three cases under consideration. MATLAB Simulink 2014, has been used for simulation. Moth Flame Optimization algorithm is used for optimizing the ITAE of the errors ACE and GCE of both the areas. For comparison, the PID controller is also applied for all the three cases. The parameters of the MFO algorithms are number of search agents, which is chosen as 30 and maximum number of iterations is chosen as 100. After several simulations, the limits on the controller gains are selected as, \(-10 \leq K_P, K_I, K_D \leq 10, 0.5 \leq \lambda_i \leq 1.5, 0.5 \leq \mu_i \leq 1.5\).
IV. SIMULATION RESULTS

The objective function, ITAE values obtained using MFO algorithm for the three cases are given in Table 5 and graphically compared in Fig.7 and values. The optimized gains achieved through MFO are depicted in Table 6 for Case 1 and Case 2. The optimized gains for Case 3 are given in Table 7.

Table 5: Comparative performance indexes of different algorithms

|       | ITAE       |
|-------|------------|
| FOPID | PID        |
| Case 1| 0.0012     |
| Case 2| 0.0156     |
| Case 3| 0.0046     |

Table 6: Controller gains tuned by optimization algorithms- Case 1 & Case 2

| Gains  | PID | FOPID |
|--------|-----|-------|
| Case 1 | Kp1 | 2     | 1.9588   |
|        | Kp2 | 2     | 4.9878   |
|        | Ki1 | 1.9040| 4.9968   |
|        | Kd1 | 1.6529| 5        |
|        | Kp11| 0.3250| 0.7693   |
|        | Kp22| 0.2699| 0.6142   |
|        | λ1  | -     | 0.9988   |
|        | λ2  | -     | 1.0002   |
|        | μ1  | -     | 0.5000   |
|        | μ2  | -     | 0.6515   |
| Case 2 | Kp1 | 1.9994| 4.9945   |
|        | Kp2 | 0.3092| 5        |
|        | Kp11| 0.2161| 0.0136   |
|        | Kp22| 0.0011| -0.7960  |
|        | Ki1 | 1.9996| 5        |
|        | Ki2 | 0.0099| 4.9973   |
|        | Kd1 | 0.0011| -0.8817  |
|        | Kd2 | 0.7010| 0.001    |
|        | Kd11| 0.8000| 5        |
|        | Kd22| 0.5325| 0.0061   |
|        | λ1  | -     | 1.4025   |
|        | λ2  | -     | 1.0043   |
|        | λ3  | -     | 1.1390   |
|        | λ4  | -     | 1.5000   |
|        | μ1  | -     | 0.5000   |
|        | μ2  | -     | 0.5000   |
|        | μ3  | -     | 1.4467   |
|        | μ4  | -     | 0.5480   |
The quantitative performance comparison of the FOPID and PID controllers are shown in Table 8 for Case 1 and Case 2. The performance indices obtained for Case 3 using PID and FOPID are compared and shown in Table 9.

**Table 7: Controller gains tuned by optimization algorithms- Case 3**

| Case 3 | Gains | FOPID | PID |
|--------|-------|-------|-----|
| $K_{p1}$ | 5     |       | 2   |
| $K_{p2}$ | 0.001 | 0.001 |
| $K_{i1}$ | 4.9934 | 1.7414 |
| $K_{i2}$ | 0.3551 | 0.001 |
| $K_{d1}$ | 5     |       | 2   |
| $K_{d2}$ | -0.7828 | -0.9989 |
| $K_{p11}$ | 5     |       | 2   |
| $K_{p22}$ | -0.2118 | 0.0001 |
| $K_{i11}$ | 0.0950 | 0.0011 |
| $K_{i22}$ | 0.001 |       | 0.0587 |
| $K_{d11}$ | 1.5277 | 1.1746 |
| $K_{d22}$ | 1.0088 | -     |
| $\lambda_1$ | 1.0047 | -     |
| $\lambda_2$ | 1.0003 | -     |
| $\lambda_3$ | 0.6352 | -     |
| $\mu_1$ | 1.4937 | -     |
| $\mu_2$ | 1.0654 | -     |
| $\mu_3$ | 0.5058 | -     |
| $\mu_4$ | 1.4629 | -     |

**Table 8: Comparison frequency deviation performance indices**

| Area | Performance Index | FOPID | PID | Rajesh [19] |
|------|-------------------|-------|-----|-------------|
| Case 1 | Area 1 | ST (s) | 7.5 | 8 | 30 |
| | | US (Hz) | -0.006 | -0.007 | -0.0800 |
| | | OS (Hz) | 0.0018 | 0.003 | 0.0400 |
| | Area 2 | ST (s) | 7.8 | 9 | 30 |
| | | US (Hz) | -0.003 | -0.004 | -0.0800 |
| | | OS (Hz) | 0.0016 | 0.0031 | 0.0400 |
| Case 2 | Area 1 | ST (s) | 7 | 10 | 45 |
| | | US (Hz) | -0.005 | -0.008 | -0.08 |
| | | OS (Hz) | 0.0023 | 0.005 | 0.06 |
| | Area 2 | ST (s) | 10 | 15 | 45 |
| | | US (Hz) | -0.003 | -0.005 | -0.08 |
| | | OS (Hz) | 0.0028 | 0.006 | 0.06 |

**Table 9: Comparison frequency deviation performance indices Case 3**

| Area | Performance Index | FOPID | PID | Rajesh [19] |
|------|-------------------|-------|-----|-------------|
| Case 3 | Area 1 | ST (s) | 7 | 13 | 55 |
| | | US (Hz) | -0.017 | -0.014 | -0.15 |
| | | OS (Hz) | 0.004 | 0.003 | 0.12 |
| | Area 2 | ST (s) | 7 | 17 | 55 |
| | | US (Hz) | -0.0065 | -0.003 | -0.15 |
| | | OS (Hz) | 0.0008 | 0.0035 | 0.12 |

**Fig. 8 Case1: Frequency deviation in Area-1**

**Fig. 9 Case1: Frequency deviation in Area-2**
The output responses obtained using FOPID and PID controllers for Case 1 are shown from Fig.8 to Fig.11. The output responses obtained using FOPID and PID controllers for Case 2 are shown from Fig.12 to Fig.15.
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Area-1 and Area-2 frequency deviations obtained using the optimized PID and FOPID gains for Case 3 are shown in Fig. 16 and Fig. 17. The tie-line power deviation and the Genco outputs are shown in Fig. 18 and Fig. 19 respectively. The Genco outputs for Case 3 are calculated and given in Table 10.

V. CONCLUSION

In this work, an effort has been made to analyze the practicability of affording optimized frequency control as an ancillary service using FOPID controller optimized by MFO algorithm in a competitive power market. The performance of FOPID controller has been compared with that of the classical PID controller in the two area interconnected non-reheat thermal power system. Three different cases under bilateral contract scenario have been analyzed. The gains of the AGC and Load following FOPID controllers are optimized by the MFO algorithm using ITAE of ACE and GCE as objective function and it has been found that FOPID is effective in bringing the frequency deviation and tie line power deviations to zero. In all the three cases, the contracted amount of power demanded by the DCs has been supplied by the corresponding GCs. On comparison of the results with that of [19], the effectiveness of FOPID controller is established.

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Appendix I

Nomenclature

| DC  | Genco |
|-----|-------|
| ΔPf | Change in Load Demand |
| Kp  | Gain of the power system |
| Tp  | Time constant of the system(s) |
| Ti  | Time constant of the turbine(s) |
| Tg  | Time constant of the Governor(s) |
| T12 | Time constant of the tie-line(s) |
| R   | Speed regulation (Hz/p.u.MW) |
| ΔF  | Frequency deviation (Hz) |
| ΔPd12 | Deviation in Tie line power exchange between Area -1 and Area-2 |
| ΔP12,UC | Un-contracted load demand |
| A1, A2 | ACE participation factors of GCs 1 & 2 in area-1 |
| A3, A4 | ACE participation factors of GCs 3 & 4 in area-2 |
| B1, B2 | Frequency bias factors |
| Kp1, Kp2, Kp3, Kp4 | Gains of Load following controller for GC2 |
| Kp2, Kp3, Kp4, Kp5 | Gains of Load following controller for GC4 |
| Kφ11, Kφ12, Kφ13, Kφ14 | Gains of AGC controller in area-1 |
| Kφ22, Kφ22, Kφ22, Kφ22 | Gains of AGC controller in area-2 |

Appendix II

Nominal Values Of System Parameters

| Kp   | 120   |
| Tm   | 0.08 s |
| Tm   | 0.3 s  |
| Tp   | 20 s   |
| R    | 2.4 Hz/p.u.MW |
| B    | 0.425  |
| Tj   | 0.0866 |

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