Optimized Price Based Frequency Regulation for Multi Area Deregulated Electricity Market

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Abstract: *- This paper demonstrates the study of a price based frequency linked regulation for three area multi-unit automatic generation control (AGC) under deregulated market scenario. In this work conventional secondary feedback control signal has been replaced through unscheduled interchange (UI) based price signal linking to the frequency at the prevailing time. The three area multi-unit power system mathematical model has been developed to incorporate the various types of transactions incident in a competitive electricity market and simulation is carried out using MATLAB/SIMULINK software. particle swarm optimization (PSO) is used in optimizing the gain of integral controller of individual generating units. Simulation results exhibit the effectiveness of PSO in the tuning of gain of integral controller along with price based frequency linked regulations for system under study.*

Keywords:Automatic Generation Control, Deregulated Electricity Market, Unscheduled Interchange, Particle Swarm Optimization

I. INTRODUCTION

Automatic generation control (AGC) is a very important issue in power system operation and control for supplying sufficient and reliable electric power with good quality. In deregulated market, AGC with load following is treated as an ancillary service that is essential for maintaining the electrical system reliability at an adequate level. The main objectives of the AGC in multi-area restructured power system are maintaining zero steady state errors for frequency deviation and accurate tracking of load contracts demanded by DISCOs.

In an open energy market, generation companies (GENCOs) may or may not participate in the AGC task. On the other hand, a distribution company (DISCOs) may contract individually with a GENCO or Independent power producers (IPPs) for power in its area or other areas and all this tasks are done under the supervision of the independent system operator (ISO) [1].

As mentioned above, after the power system restructuring, frequency regulation has become challenging job to establish good coordination between a large number of GENCOs and DISCOs. Many approaches have been presented by proficient authors in the literature [2-10] to regulate frequency under the deregulated electricity market using advanced control and evolutionary techniques like robust control, fuzzy logic, multi stage fuzzy proportional integral derivative (MSF-PID), genetic algorithm (GA), robust mixed H_2/H_∞, hybrid particle swarm optimization (HPSO), polar fuzzy, interactive artificial bee colony (IABC) optimization based fuzzy (IABCF), robust multi input multi output proportional integral derivative (MIMO-PID) and bacterial forging (BF) etc.

Frequency linked pricing is another one such approach of AGC in deregulated market that encourages generators to respond proportionally to frequency deviations or to their corresponding price signals sent out by the independent system operator (ISO) and help to restore the system frequency back to nominal or close to nominal value. Berger and Schweppe [11] demonstrated the real-time pricing of generation using the proportional integral feedback control law of frequency deviations to assist in load frequency control. J Kumar et. al. [12, 13] proposed a price based bilateral market structure and its operating mechanism using the concept of contract participation factor [12, 13]. Further more details on price based frequency regulation can be found from [14, 15].

Price based frequency regulation scheme based on unscheduled interchange signal suitable to Indian market scenario is reported in [16, 17] which are also useful to avoid or reduced unintended unscheduled interchanges (UIs) among the various participants of deregulated market. Moreover, in [18] authors have analyzed impact of UI Rate on automatic generation controller of participating generators coordination of doubly fed induction generator (DFIG) based wind energy conversion system along with unscheduled interchange based frequency control scheme has been shown in [19] while PSO based optimized price based frequency control has been reported in [20].

The aim of this article is to analyze the effectiveness of PSO, in frequency-linked pricing mechanism for frequency regulation. Rest of the article is structured as follows: Section II describes about comparison of deregulated electricity market conventional control v/s UI based control. Section III details about state space model for system under study. While section IV tells about PSO and its implementation procedure for system under study. Simulation results and analysis is covered in section V. finally; section VI carries conclusions.

To Cary out the present work, UI rate v/s frequency curve for the year 2013 issued by Central electricity regulation commission (CERC) has been used and is as shown in Fig.1 [21].

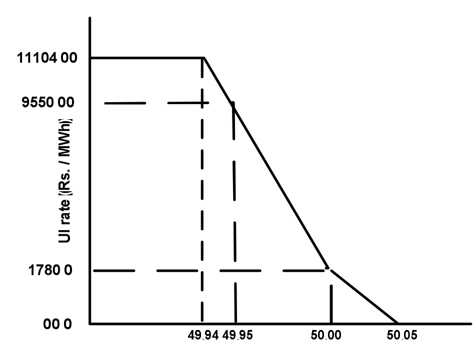


Fig. 1: UI rate v/s frequency curve (CERC, 2013) [21]

The detailed schematic of three area, ten generators and nine discos scheme has been prepared on the basis of frame work done in [16, 17] and shown in Fig.2.

II. DEREGULATED ELECTRICITY MARKET CONVENTIONAL CONTROL V/S UI BASED CONTROL

In traditional multi area deregulated scenario, Area control error (ACE) signal has to be distributed among no. of generators in the area as in proportion to their participation in the AGC. Coefficient that distributes ACE to several GENCOs is termed as "ACE participation factor" (APF). Note that,

$$\sum_{i=1}^{n} \mathrm{apf}_i = 1 \text{ where n = total no. of GENCOs.} \quad (1)$$

Also, the scheduled steady state power flow on the tie line is given as

$$P_{\text{tie k m, scheduled}} = \left\{\begin{matrix}\text{Demand of DISCOs in area m from} \\ \text{GENCOs in area k}\end{matrix}\right\} - \left\{\begin{matrix}\text{Demand of DISCOs in area k from} \\ \text{GENCOs in area m}\end{matrix}\right\} \quad (2)$$

At any given time, the tie line power error $\Delta P_{\text{tie k-m, error}}$ is:

$$\Delta P_{\text{tie k-m, error}} = P_{\text{tie k-m, actual}} - P_{\text{tie k-m, scheduled}} \quad (3)$$

$\Delta P_{\text{tie k-m,}}$ error vanishes in the steady state as the actual tie line power flow reaches the scheduled power flow. This error signal is used to generate the respective ACE signals.

$$\text{i.e. } ACE_k = B_k * \Delta f_k + \Delta P_{\text{tie k-m,error}}\ , \quad (4)$$

Where, k,m= no. of Area

$$\text{Also, } \Delta P_{\text{tie k-m, error}} = -\frac{P_{rk}}{P_{rm}} * \Delta P_{\text{tie m-k, error}} \quad (5)$$

Where, P_{rk} and P_{mj}= area rated power

$$\text{Also } \alpha_{km} = \frac{P_{rk}}{P_{rm}} \quad (6)$$

Unlike in traditional deregulated system, in UI based secondary control no. of generators of each area receives an individual error signal named as generation control error (GCE) [17] which is the output signal of each GCE block in Fig. 2. Each generator of three areas participates in AGC and their participation depends upon GCE signal.

GCE_i = output of GCE block, i= no. of generators (7)

Detailed logic of GCE block is as follows:

Input of GCE block is the difference of UI rate signal (ρ) and marginal cost signal (γ_i) of each unit. In GCE block these two signals have been compared with following logic:

```
if γi> ρ0; Where ρ0=1780 Rs. /MWh at 50Hz.
   if ρ > γi ;
GCEi= ρ - γi ;
          else if ρ < ρ0;
GCEi = γi - ρ0;
          else GCEi =0;
    end
           else
                if ρ < γi
                     GCEi= ρ – γi ;
        else if GCEi> ρ0
GCEi = ρ – ρ0;
           else
GCEi =0;
        end
end
```

(8)

Also, the logic of F to UI block of Fig.1 is as follows:

```
if   f<= 49.94
        ρ =11104
    else if   f<=50
          ρ =1780+155400*(50-f)
               else if f<=50.05
                      ρ = 35600*(50.05-f)
                  else
                      ρ =0
           end
end
```

(9)

Few important findings of UI based control:

- There would be no frequency bias or tie line bias in net interchange schedule [22].
- The required collective action for correction of frequency (only improvement of frequency in this case) would be induced through the pricing of UI, rather than through frequency bias as in ACE [22].
- Control areas would be only notional, in the sense that it would not be mandatory for them to absorb their own load changes fully. Hence there would be no requirement for the control areas to maintain their actual interchanges close to their net interchange schedules and also, no need to reduce generation control error (GCE) to zero every ten minutes as the case in ACE [20].
- The actual interchange can remain deviated from the net interchange schedule; because here we are pricing the deviations and hence GCE signal does not drive steady state frequency error to zero but depends on slope of UI curve, if curve is steeper (slope at nominal frequency very large) frequency error goes nearer to zero [22].
- The concept of contract participation factor matrix (CPF) remains unchanged.

III. STATE SPACE EQUATIONS FOR THREE AREA SYSTEM

The proposed system is a three area system with ten Generators and nine Discos. A state space model is prepared by taking Fig.2 as a reference and written in the form as:

$$\dot{x} = Ax + Bu + Fw + P\gamma \quad (10)$$

For the proposed model the system is of 46th Order.

The order of matrix A = 46×46, x = 46× 1, B= 46 X10, u = 10 X 1, F = 46X10, w =9X1, P =46X 3, $\gamma = 3 \times 1$.

Sate variables:

x= [X1=Δf1, X2=Δf2, X3=Δf3, X4= ΔPtie12, X5=ΔPtie13, X6=ΔPtr1, X7=ΔPt1, X8=ΔPgov1, X9=ΔPtr2, X10=ΔPt2, X11=ΔPgov2, X12=ΔPtr3, X13=ΔPt3, X14=ΔPgov3, X15=ΔPtr4, X16=ΔPt4, X17=ΔPgov4, X18=Δgce1dt; X19=Δgce2dt; X20=Δgce3dt; X21=Δgce4dt; X22=ΔPtr5, X23=ΔPt5, X24=ΔPgov5, X25=ΔPtr6, X26=ΔPt6, X27=ΔPgov6, X28=ΔPtr7, X29=ΔPt7, X30=ΔPgov7, X34=ΔPtr8, X35=ΔPt8, X36=ΔPgov8, X37=ΔPtr9, X38=ΔPt9, X39=ΔPgov9, X40=ΔPtr10, X41=ΔPt10, X42=ΔPgov10, X46=ΔPtie23]

Control Inputs:
u1=ki1*∫Δgce1dt, u2=ki2*∫Δgce2dt, u3=ki3*∫Δgce3dt, u4=ki4*∫Δgce4dt, u5= ki5*∫Δgce5dt, u6= ki6*∫Δgce6dt, u7= ki7*∫Δgce7dt, u8= ki8*∫Δgce8dt, u9= ki9*∫Δgce9dt, u10 =ki10*∫Δgce10dt.

Disturbance Inputs (contracted demand of various Discos from Various Gencos of three area system):
d1=ΔPDisco1, d2= ΔPDisco2, d3=ΔPDisco3, d4=ΔPDisco4, d5=ΔPDdisco5, d6=ΔPDdisco6, d7=ΔPDisco7, d8=ΔPDisco8, d9=ΔPDisco9.
Disturbance Inputs (Uncontracted demand of various Discos from Gencos of their area):
duc1=ΔPuc1, duc2=ΔPuc2, duc3=ΔPuc3.
State equations:
From the transfer function blocks labeled for area 1 are:
Block1:
$$\dot{x}_1 = -\frac{1}{T_{ps1}}x_1 - \frac{K_{ps1}}{T_{ps1}}x_4 - \frac{K_{ps1}}{T_{ps1}}x_5 + \frac{K_{ps1}}{T_{ps1}}x_6 + \frac{K_{ps1}}{T_{ps1}}x_9 + \frac{K_{ps1}}{T_{ps1}}x_{12} + \frac{K_{ps1}}{T_{ps1}}x_{15} + \frac{K_{ps1}}{T_{ps1}}(d_1 + d_2 + d_3 + d_4 + d_{uc1})$$
Block4:
$$\dot{x}_4 = 2\pi T_{12}x_1 - 2\pi T_{12}x_2$$
Block5:
$$\dot{x}_5 = 2\pi T_{13}x_1 - 2\pi T_{13}x_3$$
Block6:
$$\dot{x}_6 = -\frac{1}{T_{r1}}x_6 + \left(\frac{1}{T_{r1}} - \frac{K_{r1}}{T_{t1}}\right)x_7 + \frac{K_{r1}}{T_{t1}}x_8$$
Block7:
$$\dot{x}_7 = -\frac{1}{T_{t1}}x_7 + \frac{1}{T_{t1}}x_8$$
Block8:
$$\dot{x}_8 = -\frac{1}{R_1 * T_{gov1}}x_1 - \frac{1}{T_{gov1}}x_8 + \frac{1}{T_{gov1}}u_1 + (DP_1 + DP_2 + DP_3)\frac{1}{T_{gov1}}$$
Block9:
$$\dot{x}_9 = -\frac{1}{T_{r2}}x_9 + \left(\frac{1}{T_{r2}} - \frac{K_{r2}}{T_{t2}}\right)x_{10} + \frac{K_{r2}}{T_{t2}}x_{11}$$
Block10:
$$\dot{x}_{10} = -\frac{1}{T_{t2}}x_{10} + \frac{1}{T_{t2}}x_{11}$$
Block11:
$$\dot{x}_{11} = -\frac{1}{R_2 * Tgov2}x_1 - \frac{1}{T_{gov2}}x_{11} + \frac{1}{T_{gov2}}u_2 + (DP_4 + DP_5 + DP_6)\frac{1}{T_{gov2}}$$
Block12:
$$\dot{x}_{12} = -\frac{1}{T_{r3}}x_{12} + \left(\frac{1}{T_{r3}} - \frac{K_{r3}}{T_{t3}}\right)x_{13} + \frac{K_{r3}}{T_{t3}}x_{14}$$
Block13:
$$\dot{x}_{13} = -\frac{1}{T_{t3}}x_{13} + \frac{1}{T_{t3}}x_{14}$$
Block14:
$$\dot{x}_{14} = -\frac{1}{R_3 * Tgov3}x_1 - \frac{1}{T_{gov3}}x_{14} + \frac{1}{T_{gov3}}u_3 + (DP_7 + DP_8 + DP_9)\frac{1}{T_{gov3}}$$
Block15:
$$\dot{x}_{15} = -\frac{1}{T_{r4}}x_{15} + \left(\frac{1}{T_{r4}} - \frac{K_{r4}}{T_{t4}}\right)x_{16} + \frac{K_{r4}}{T_{t4}}x_{17}$$
Block16:
$$\dot{x}_{16} = -\frac{1}{T_{t4}}x_{16} + \frac{1}{T_{t4}}x_{17}$$
Block17:
$$\dot{x}_{17} = -\frac{1}{R_4 * Tgov4}x_1 - \frac{1}{T_{gov4}}x_{17} + \frac{1}{T_{gov4}}u_4 + (DP_{10} + DP_{11} + DP_{12})\frac{1}{T_{gov4}}$$
Block18:
$$\dot{x}_{18} = \dot{u}_1 = K_{i1} * \Delta gce_1$$
Block19:
$$\dot{x}_{19} = \dot{u}_2 = K_{i2} * \Delta gce_2$$
Block20:
$$\dot{x}_{20} = \dot{u}_3 = K_{i3} * \Delta gce_3$$
Block21:
$$\dot{x}_{21} = \dot{u}_4 = k_{i4} * \Delta gce_4$$

IV. PARTICLE SWARM OPTIMIZATION

Particle swarm optimization (PSO) is a fast, simple and efficient population based optimization method which was proposed by Eberhart and Kennedy (1995) [23, 24]. It has been motivated by the behavior of organisms such as fish schooling and bird flocking. In PSO, a swarm consists of number of particles which represent the possible solutions. The co-ordinates of each particle are associated with two vectors, namely the position (S_j) and velocity (V_j) vectors. The size of both vectors is same as that of the problem space dimension. All particles in a swarm fly in the search space to explore optimal solutions. Each particle updates its position based upon its own best position, global best position among particles and its previous velocity vector according to the following equations:

$$V_j^{k+1} = W * V_j^k + C_1 * Rand_1() * (P_{besti} - S_j^k) + C_2 * Rand_2() * (G_{best} - S_j^k) \quad (11)$$

$$S_j^{k+1} = S_j^k + (k)\, V_j^{k+1} \quad (12)$$

$$k = \frac{2}{\left|2 - \varphi - \sqrt{\varphi^2 - 4\varphi}\right|}, \quad \varphi \geq 4 \quad (13)$$

$$W = W_{max} - \frac{W_{max} - W_{min}}{Iter_{max}} * Iter \quad (14)$$

Where, k is constriction factor to insure convergence of the PSO.

PSO implementation for optimization of gain Ki:

Optimization of gain of integral controller of each unit in muti area is done using Integral Square Error (ISE) criterion. Required objective function of UI based AGC scheme is the minimization of sum of total Generation Control Error (GCE) plus sum of total tie line power error. Generalized objective function used for multi area scheme is,

$$J = \min\left\{\sum_{i=1}^{n} gce_i^2 + k_1 * \sum \Delta P^2{}_{tie\ k-m,error}\right\} \quad (15)$$

k_1 = weighing factor in the range 10^5 multiply with$\sum \Delta P^2(\text{tie k} - \text{m, error})$ to make mutual competitive during optimization with$\sum_{i=1}^{n} gce_i^2$.

Steps of PSO algorithm implemented for optimization of gain $K_{i\,(i=1\text{ to }10)}$ are as follow:

- Initialize real coded particles (K_i gains) of n population for each K_i. For case under consideration i=1 to 10.
- Evaluate objective function for all particles as per equation (15).
- Search for global minimum of objective function 'J 'and its corresponding global best particle G_{best} and individual best particle P_{bestj} for all particles.
- Generate new population using eq. (11), (12), (13) and (14).
- Make comparison with previous iteration data and update global best position.
- Update iteration counter and go to step 2 until iteration counter reaches to its maximum value.

V. SIMULATION AND RESULT ANALYSIS

Simulations are carried out for different test cases of the possible contracts under large load demands and disturbances. The scheduled load of discos in different areas,
ΔPDisco1= 0.1p.u., ΔPDisco2=0.1p.u., ΔPDisco3=0.05p.u. ΔPDisco4=0.05p.u. ΔPDisco5=0.1 p. u., ΔPDisco6=0.1 p. u., ΔPDisco7=0.1 p. u., ΔPDisco8= 0.05p.u. ΔPDisco9=0. 05p.u the un-contracted load in area one is ΔPuc1= 0.06p.u.

The total generation required of individual GENCOs can be calculated as:

$$\Delta Pgi = \sum_{j=1}^{N=9} CPF_{ij} * d_j + \Delta gce_i * d_{ucj} \tag{16}$$

The mutual scheduled tie-line power flows among the areas can be represented by the following formulae:

$$P_{\text{tie }1-2} = \sum_{i=1}^{4=\text{no of gencos of area1}} \sum_{j=5}^{6\text{ no of discos of area2}} CPF_{ij} * d_j - \sum_{i=5}^{7=\text{no of gencos of area2}} \sum_{j=1}^{4\text{no of discos of area1}} CPF_{ij} * d_j \tag{17}$$

$$P_{\text{tie }2-3} = \sum_{i=5}^{7=\text{no of gencos of area2}} \sum_{j=7}^{9\text{ no of discos of area 3}} CPF_{ij} * d_j - \sum_{i=8}^{10=\text{no of gencos of area3}} \sum_{j=5}^{6\text{no of discos of area2}} CPF_{ij} * d_j \tag{18}$$

$$P_{\text{tie }1-3} = \sum_{i=1}^{4=\text{no of gencos of area1}} \sum_{j=7}^{9\text{ no of discos of area3}} CPF_{ij} * d_j - \sum_{i=5}^{7=\text{no of gencos of area2}} \sum_{j=1}^{4\text{no of discos of area1}} CPF_{ij} * d_j \tag{19}$$

The necessary system data is given in **Annexure.**

Test Case A. Poolco based transactions:

In this scenario GENCOs participate in automatic generation control of their own areas only. It is assumed that large step contracted loads are simultaneously demanded by DISCOs of areas one, two and three. A case of Poolco based contracts between DISCOs and available GENCOs is simulated based on the following contract participation factor matrix(CPF). The magnitude of the elements of CPF matrix (*cpfs*) are corresponds to the fraction of the total load power contracted by Discoj (=1, 2, 3…j) from a Gencoi (=1, 2, 3…n).

$$CPF_p = \begin{bmatrix} 0.1 & 0.3 & 0.5 & 0.5 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.3 & 0.2 & 0.2 & 0.1 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.3 & 0.2 & 0.2 & 0.2 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.3 & 0.3 & 0.1 & 0.2 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 02 & 0.2 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.4 & 0.4 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.4 & 0.4 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.6 & 0.5 & 0.5 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.2 & 0.25 & 0.3 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.2 & 0.25 & 0.2 \end{bmatrix} \tag{20}$$

In the steady state, tie-line power flow errors, frequency deviations and hence the generation control errors of all the generators of each area driven back nearly to zero. The generated powers properly converge to the specified scheduled values.

Test Case B. Combination of Poolco and Bilateral based transactions:

In this case, any DISCO has the freedom to have a contract with any GENCO in its own and other areas. It is assumed that all the DISCOs contract with the available GENCOs for power as per the following CPF_b.

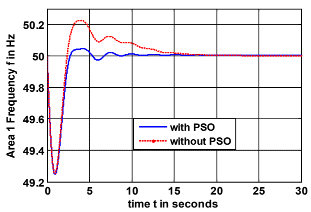
$$CPF_b = \begin{bmatrix} 0.25 & 0.2 & 0.15 & 0.10 & 0.0 & 0.1 & 0.0 & 0.0 & 0.25 \\ 0.2 & 0.2 & 0.15 & 0.125 & 0.1 & 0.1 & 0.0 & 0.0 & 0.0 \\ 0.25 & 0.2 & 0.15 & 0.125 & 0.1 & 0.1 & 0.2 & 0.0 & 0.0 \\ 0.1 & 0.1 & 0.15 & 0.3 & 0.0 & 0.0 & 0.0 & 0.1 & 0.0 \\ 0.025 & 0.025 & 0.0 & 0.0 & 0.1 & 0.1 & 0.0 & 0.0 & 0.0 \\ 0.05 & 0.05 & 0.1 & 0.1 & 0.2 & 0.2 & 0.15 & 0.25 & 0.15 \\ 0.025 & 0.025 & 0.1 & 0.0 & 0.05 & 0.1 & 0.1 & 0.2 & 0.1 \\ 0.1 & 0.05 & 0.05 & 0.15 & 0.15 & 0.2 & 0.3 & 0.2 & 0.4 \\ 0.0 & 0.05 & 0.10 & 0.05 & 0.1 & 0.1 & 0.2 & 0.2 & 0.1 \\ 0.0 & 0.1 & 0.05 & 0.05 & 0.2 & 0.0 & 0.05 & 0.05 & 0.0 \end{bmatrix} \tag{21}$$

Table I. Steady state values for test case B

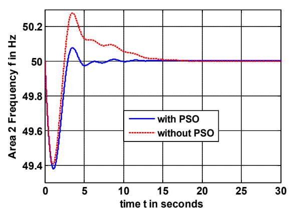
	Computed value	**Simulation value**	**Error**	**Optimal value of K_{Ii}**
Case B:				
Area 1 frequency in (Hz)	50.0000	50.00236	-0.0023	-
Area 2 frequency in (Hz)	50.0000	50.00238	-0.0023	-
Area 3 frequency in (Hz)	50.0000	50.00236	-0.0023	-
ΔPg1 in (MW)	254.00	254.26	-0.26	0.0003
ΔPg2 in (MW)	234.7500	235.35	-1.	0.0002
ΔPg3 in (MW)	303.7500	303.18	0.57	0.0002304
ΔPg4 in (MW)	157.5000	157.39	0.11	0.0003
ΔPg5 in (MW)	69.0000	69.16	-0.16	0.00009
ΔPg6 in (MW)	263.0000	263.11	-0.11	0.0001947
ΔPg7 in (MW)	138.0000	138.14	-0.14	0.0001334
ΔPg8 in (MW)	332.0000	331.9	0.1	0.0003178
ΔPg9 in (MW)	185.5000	185.39	0.11	0.0001
ΔPg10 in (MW)	122.5000	123.24	-0.74	0.0002583
Ptie1-2 in (MW)	11	13.23	-2.23	-
Ptie1-3 in (MW)	-81	-83.5	2.5	-
Ptie2-3 in (MW)	-39	-37	-2	-

Table I indicate all the parameter values in numerical with comparison of calculated and simulated data and optimal value of gain of integral controllers for test case B. Fig. 3[a-c] shows the all three area frequency response which settles close to

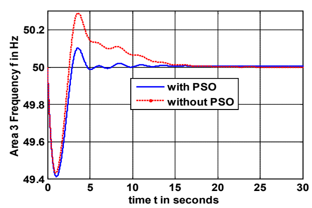
50Hz value in steady state on account of large slope of selected UI curve. Also, with optimized gain controllers' transient response of each area frequency curve have been improved. Fig. 3(d-f) shows the response of actual power on the tie line. It is observed that with PSO actual tie line power settles reasonably close to its corresponding desired value which also confirms the satisfactory operation of UI based control in multi area deregulated market system. Though small deviation has been observed this is due to absence of tie line bias control. Fig.3(g) shows response of actual generated powers of the GENCOs for with and without PSO optimized gain. The final generation values of GENCOs with PSO optimized gain case are quite nearer to the desired generation in the steady state following optimum response. While Fig.3 (h) indicates the response of GCE error for with and without PSO optimized gain of integral controller of each unit. All units' GCE error response is improved with optimized gain values which show evidence of reduction of unnecessary UI exchange of power.



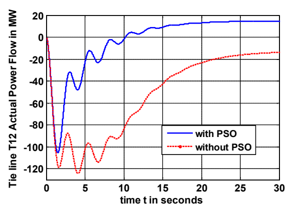
(a)Area one frequency



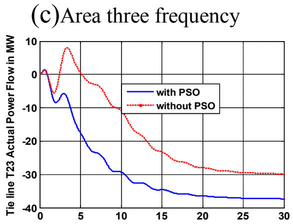
(b)Area two frequency

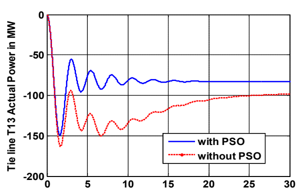


(c)Area three frequency

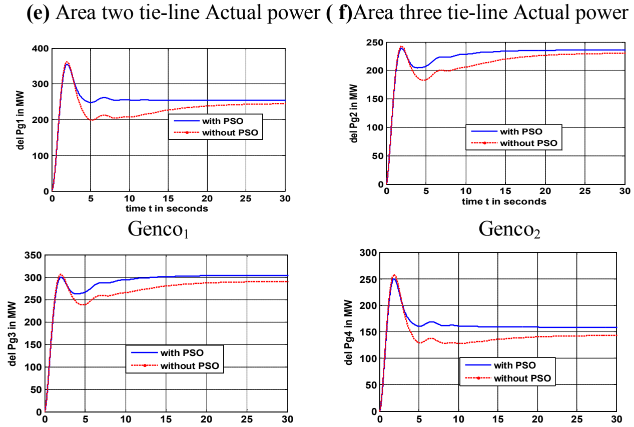


(d)Area one tie-line Actual power

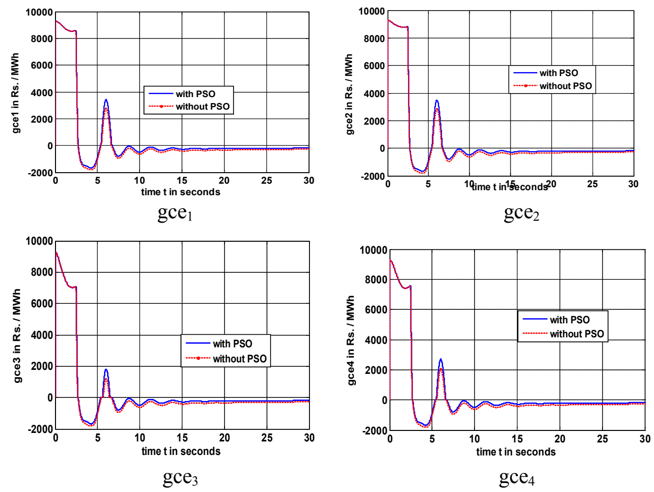




(e) Area two tie-line Actual power **(f)**Area three tie-line Actual power



(g) Change in generated power of various Genco$_s$ of Area one



h)Generation control error of various GENCOs of Area one

Fig. 3 Simulation results of bilateral based transaction (Case B)

Test Case C. Contract Violation

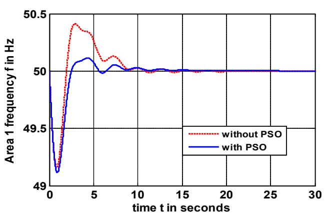
In this case, DISCOs may violate a contract by demanding more power than that specified in the contract. This excess power is reflected as a local load of the area (un-contracted demand). So to simulate this case again test case B has been considered with a modification that DISCOs of area one demands 0.06 pu of excess power. 'CPF_b' matrix is the same as in test case B. The scheduled incremental tie-line powers remain the same as in test case B in the steady state. Un-contracted load of the area one DISCOs is taken up by the GENCOs of its own area according to error signal received from their individual GCE block in steady state by following the merit order dispatch.

Table II Steady state values for Test Case C:

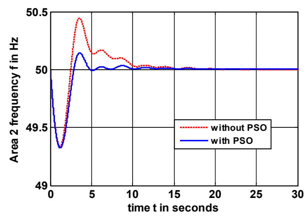
	Computed value	**Simulation value**	**Error**	**Optimal value of KI_i**
	Case C:			
Area 1 frequency in (Hz)	50.000	50.000	0.00	-
Area 2 frequency in (Hz)	50,000	50,000	0.00	-
Area 3 frequency in (Hz)	50.000	50.000	0.00	-
ΔPg1 in (MW)	332.12 (254+ 78.12)	331.62 (254+ 77.62)	0.50	0.009
ΔPg2 in (MW)	312,82 (234.75+ 78.12)	311.65 (234.75+ 6.90)	1.17	0.0085
ΔPg3 in (MW)	325.63 (303.75+ 21.88)	324.04 (303.75+ 20.30)	1.59	0.004
ΔPg4 in (MW)	179.38 (157.50+ 21.88)	178.06 (157.5+ 20.56)	1.32	0.0034
ΔPg5 in (MW)	69.00	69.97	-0.97	0.000070
ΔPg6 in (MW)	263.00	263.75	-0.75	0.000058
ΔPg7 in (MW)	138.00	138.79	-0.79	0.000060
ΔPg8 in (MW)	332.00	332.57	-0.57	0.00006
ΔPg9 in (MW)	185.50	186.13	-0.13	0.00006
ΔPg10 in (MW)	122.50	123.00	-0.5	0.0001
Ptie1-2 in MW)	11	11.00	0.0	-
Ptie1-3 in MW)	-81	-85.63	4.63	-
Ptie2-3 in MW)	-39	-36.48	-2.52	-

Table II indicates the all parameter values in numerical with comparison of calculated and simulated data and optimal value of gain of integral controllers for test case c.

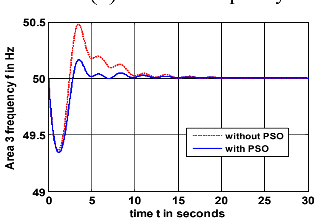
Set of Fig. 4 (a-h) shows the waveforms of various parameters for test case C. All parameters follow its desired values in steady state.Fig.4 (g) shows the generation response of GENCOs of area one following a load change in area one. They respond to the load perturbation (contracted & uncontracted) and increase their generations. Also the uncontracted demand of DISCOs of area one is taken up by the same area GENCOs by following the merit order dispatch as they receive the error signal which is the difference of UI rate and their marginal cost signal [16, 17,20]. The purpose of this work is to test the effectiveness of the proposed control against un-contracted load disturbances.



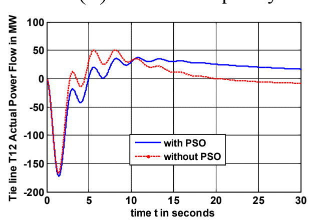
(a)Area one frequency



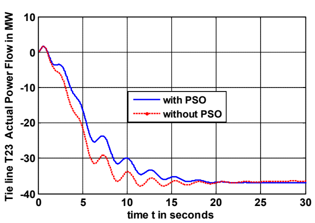
(b)Area two frequency



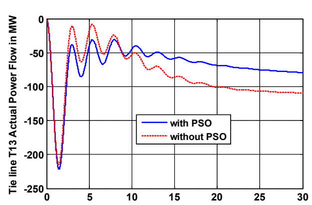
(c)Area three frequency



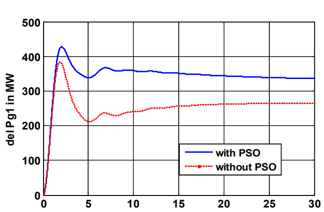
(d)Area one tie-line Actual power



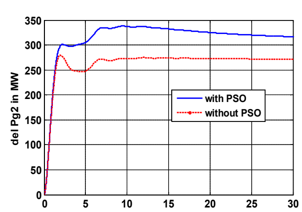
(e) Area two tie-line Actual power



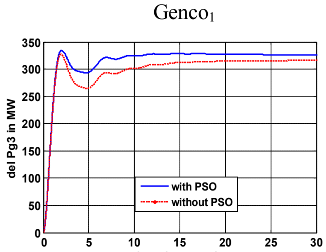
(f) Area three tie-line actual power



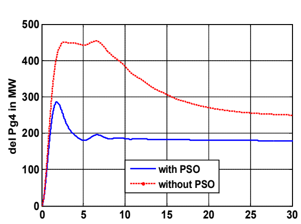
$Genco_1$



$Genco_2$

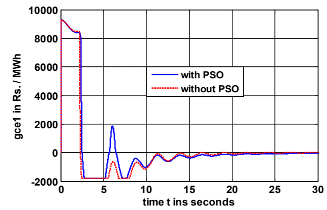


$Genco_3$

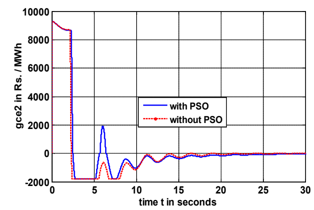


$Genco_4$

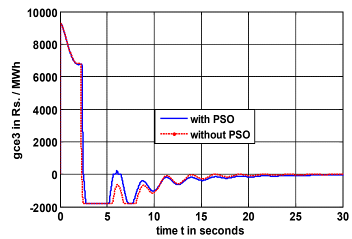
(g) Change in generated power of various $Genco_s$ of Area one



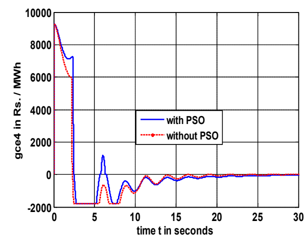
gce_1



gce_2



gce_3



gce_4

h)Generation control error of various GENCOs of Area one

Fig. 4 Simulation results of bilateral with contract violation based transaction (Case C)

VI. CONCLUSIONS

Price based frequency control gives the similar performance as the conventional control in deregulated market. The state space model for proposed scheme has been investigated. GCE signal of each GENCOs does not drive steady state frequency error to zero but it depends on slope of UI curve. In present work UI rate v/s frequency curve is fairly large so frequency error goes very close to zero. It has been also observed that tie lines actual power remains slight deviated in both the case due to absence of tie line bias control. Classical particle swarm optimization technique is used to get optimal value of gain of integral controller of individual GENCOs. It has been revealed from the simulation results that optimized gain of integral controller saves the unnecessary UI exchange and gives optimal performance in all the cases. Last but not least this proposed control is suitable for the generation deficient country like India, as real time frequency signal can be easily available on any wall socket.

REFERENCES

[1] Donde, V., Pai, M. A., Hiskens, A.I.: *Simulation and optimization in an AGC system after deregulation.* In: IEEE Trans. Power Syst., 16 (1990), No. 3, August 1990, p.481–489, U.S.A.

[2] Tyagi, B., Srivastava, S.C.: *A Decentralized automatic generation control scheme for competitive electricity markets.* In: IEEE Trans. Power Syst., 21(2006), No. 1, February 2006, p 312-320, U.S.A.

[3] Shayeghi, H., Shayanfar, H.A., Jalili, A.: *Multi-stage fuzzy PID power system automatic generation controller in deregulated environments*. In: Energy Conversion and Management, 47(2006), No.18-19, November 2006, p. 2829-2845, Elsevier, Netherlands.

[4] Demiroren, A., Zeynelgil, H.L.: *GA application to optimization of AGC in three-area power system after deregulation.* In: Int. Journal of Electrical Power & Energy

Systems, 29(2007), No. 3, March 2007, p. 230-240, Elsevier, Netherlands.
[5] Shayeghi, H., Jalili, A., Shayanfar, H.A.: *A robust mixed H2/H∞ based LFC of a deregulated power system including SMES*. In: Energy Conversion and Management, 49(2008), No.10, October 2008, p. 2656-2668, Netherlands.
[6] Bhongade, S., Gupta, H.O., Tyagi, B.: *Genetic Algorithm based PID controller for Frequency Regulation Ancillary services.* In: Int. Journal of Engineering Science and Technology, 2(2010), No. 12, March 2010, p. 6902-6908.
[7] Bhatt, P., Roy, R., Ghoshal, S.P.: *Optimized multi area AGC simulation in restructured power systems.* In: Int. Journal of Electric Power Energy Syst., 3(2010), No. 4, June 2010, p. 311–322, Netherlands.
[8] Pratap, G.R., Umrao, R., Chaturvedi, D.K.: *Automatic generation control with polar fuzzy controller considering generation rate constraint in deregulated power system*. In: Advances in Engineering, Science and Management, p March 2012, p. 610 – 615, Netherlands.
[9] Wadhwa, K., Raja, A., Gupta, S.K.: *BF based integral controller for AGC of multi area thermal system under deregulated environment.* In: Proceedings of IEEE Power India Conference, December. 2012, p. 1- 6.
[10] Javidan, J., Ghasemi. *A novel fuzzy RPID controller for multi area AGC with IABC optimization*. In: Journal of Engineering, 2013 (2013), Article ID 510572, p. 1-13, U.K.
[11] Berger, W., Schweppe, F.C.: *Real-time pricing to assist in load frequency control*. In: IEEE Trans. Power Syst., 4(1989), No. 3, August 1989, p. 920–926, USA.
[12] Kumar, J., Ng, K., Sheble, G.: *AGC simulator for price-based operation Part I*. In: IEEE Trans. Power Syst., 12(1997), No. 2, May 1997, p.527-532, USA.
[13] Kumar, J., Ng, K., Sheble, G.: *AGC simulator for price-based operation Part II*. In: IEEE Trans. Power Syst., 12(1997), No. 2, May 1997, p.533-38, USA.
[14] Zhong, J., Bhattacharya, K.: *Frequency linked pricing as an instrument for frequency regulation in deregulated electricity markets.* In: Proceedings of IEEE Power Engineering Society Summer Meeting, July 2003, p. 566-571.
[15] Zhao, H., and Bhattacharya, K.: *"Design of frequency regulation service market based on price and demand elasticity bids.* In: 15th Power Systems Computation Conference (PSCC), Liege, Belgium, 22–26 August 2005, Session 11, paper 3, p 1-7.
[16] Tyagi, B., Srivastava, S.C.: *A mathematical framework for frequency-linked availability-based tariff mechanism in India*. In: Proceedings of 13th National Power Systems Conference (NPSC), December 2004, IIT Chennai, India, Vol. 1, p. 516-521.
[17] Chanana, S., Kumar, A.: *A price based automatic generation control using unscheduled interchange price signals in Indian electricity system*. In: Int. Journal of Engineering, Science and Technology, 2(2010), No. 2, April 2010, p. 23, Singapore.
[18] Pujara, S.M., Kotwal, C.D.: *Impact of UI Rate on Automatic Generation Controller of Participating Generators under Frequency Linked Tariff System.* In: Journal of Electrical Engineering, 14(2014), No.4, Dec.,2010, p.1-9, Romania.
[19] Verma, Y.P., Kumar, A.: *Participation of Doubly Fed Induction Generator Based Wind Turbine in Frequency Regulation with Frequency linked Pricing. In:* Electric Power Components and Systems, 40(2012), No.3, October 2012, p. 1586–1604, London.
[20] Pujara, S.M., Kotwal, C. D.: *Optimized integral gain controllers for price based frequency regulation of single area multi-unit power system.* In: Int. Journal on Electrical Engineering and Informatics, 6(2014), No.2, April, 2014, p.306-323, Indonesia.
[21] Unscheduled Interchange notification (draft)No. L-1/ 132/2013/CERC., CERC, New Delhi, June 2013.
[22] Bhushan, B., Roy, A., Pentayya, P.: *The Indian medicine.* In: Proceedings of IEEE Power Engineering Society General Meeting, Denver, USA, p. 2236-2239, June 2004.
[23] Kennedy, J., Eberhart, R.C.: *Particle swarm optimization.* In Proceedings of IEEE Int. Conf. on Neural Networks (Perth, Australia), IEEE Service Center, Piscataway, NJ, p. 1942- 1948, 1995.
[24] Eberhart, R.C., Kennedy, J.: *A new optimizer using particles swarm theory.* In: Proceedings of 6th Int. Symposium on Micro Machine and Human Science, Nagoya-Japan, IEEE Service Center, NJ, p.39-43, 1995.
[25] Bevrani, H.: *Robust power system frequency control,* Springer, 2009.

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ANNEXURE

PSO Input Parameter	
No. of population: n_{pi} (i=1to10)	100
$iter_{max}$	200
$C_1=C_2$	1.05
W_{max}	0.7
W_{min}	0.3
k (constriction factor)	0.38

System Data										
Area	**1**				**2**				**3**	
Generator unit	**G1**	**G2**	**G3**	**G4**	**G5**	**G6**	**G7**	**G8**	**G9**	**G10**
Rating(MW)	1200	600	800	800	600	1200	800	1400	600	600
H_i(s)	6	4	5	5	5	5	4	6	5	5
D_i (pu/Hz)	0.05	0.08	0.05	0.04	0.05	0.08	0.05	0.07	0.05	0.04
R_i (%)	3	3	3.2	2.7	2.7	2.6	2.5	2.8	3.0	3.0
T_{ti} (sec)	0.40	0.36	0.42	0.45	0.44	0.32	0.40	0.30	0.40	0.41
T_{gi} (sec)	0.3	0.2	0.07	0.1	0.3	0.2	0.15	0.15	0.15	0.2
T_{ri} (sec)	4.2	4.2	4.2	4.2	4.0	4.0	4.0	4.3	4.3	4.3
Reheat Gain Kr_i	0.34	0.34	0.34	0.34	0.32	0.32	0.32	0.33	0.33	0.33
T_{kj} (pu /Hz)	T_{12}=0.2				T_{21}=0.2			T_{31}=0.25		
	T_{13}=0.25				T_{23}=0.12			T_{32}=0.12		
Base power (MW)	3400									
Cost coefficient	**Generators Cost Data**									
b (Rs./MWh)	671	1450	732	488	610	871	700	800	1400	732
c (Rs./MW^2h)	1.0675	1.0675	3.8125	3.8125						
	Initial Generation Scheduling Data									
PG_i^0 in (MW)	528.8	163.93	140.07	172.07	410.94	458.54	377.04	500	210.81	146

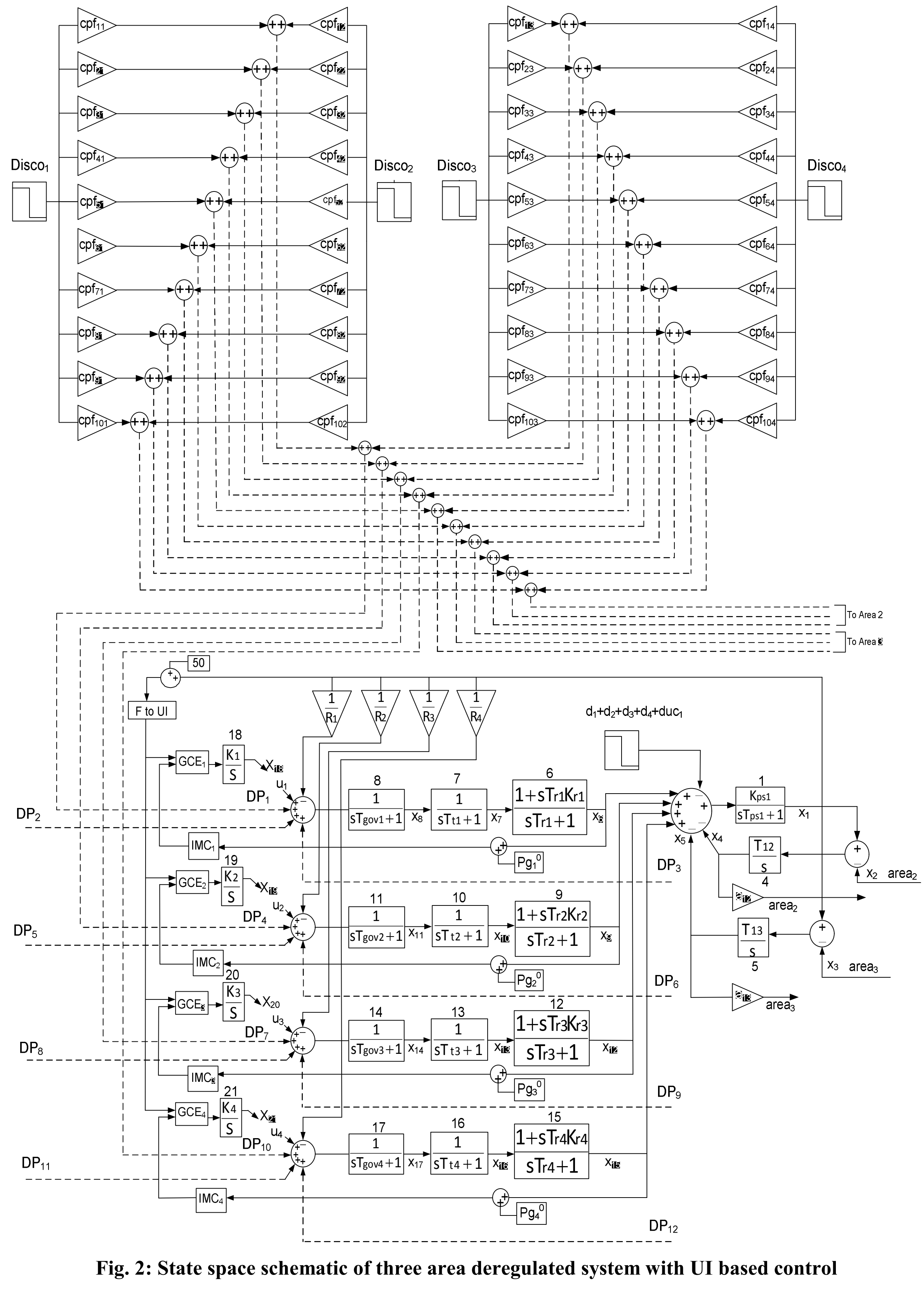

Fig. 2: State space schematic of three area deregulated system with UI based control