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Harmony Search Algorithm in Optimal Design of Load Frequency Controller in Deregulated Environment

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Abstract: This paper presents the performance of Fuzzy Proportional plus Derivative Controller, Fuzzy Proportional plus Integral Controller and Fuzzy Proportional plus Integral and Derivative Controllers on Load frequency Problem. The present work better utilizes the Harmony Search Algorithm to design the optimal parameters of Fuzzy PID (FPID) Controllers by using both conventional PID tuning and Harmony search algorithm based tuning. Traditional two area power system is restructured and implemented in deregulated environment to account the effect of contracted and un-contracted power demands on system dynamics. An interconnected power system having same identical areas is considered for analysis.

Keywords: Load Frequency Control, Proportional plus Integral plus Derivative Controller, Harmony search algorithm (HSA) optimization, DISCOM'S, GENCO'S

I. Introduction

Electricity industry deregulation is often described as the increase in economic efficiency of the electricity industries through a change in industry managements by reducing direct government involvement. In restructured power systems, load frequency control is intricate to predict and hence, received increased attention and need to identify automatic generation or load frequency control as an auxiliary service that must be provided by generation companies. For large scale electric power systems with interconnected areas, Load Frequency Control (LFC) is important to keep the system frequency and the inter-area tie power as near to the scheduled values as possible. The input mechanical power to the generators is used to control the frequency of output electrical power and to maintain the power exchange between the areas as scheduled. A well designed and operated power system must cope with changes in the load and with system disturbances, and it should provide acceptable high level of power quality while maintaining both voltage and frequency within tolerable limits [1].

To control load frequency of power systems, various controllers are used in different areas, but due to non-linearity's in the system components and alternators, these controllers cannot control the frequency quickly and efficiently Load Frequency Control problem (LFC) is the major requirement in parallel operation of several interconnected power systems. Whenever load on the power system is increased, the turbine speed drops before the governor can adjust the input to the new load. The perturbation of frequencies at the areas and resulting tie-line power flows arise due to unpredictable load variations that cause mismatch between the generated and demanded powers. The objective of LFC is to minimize the transient deviations and to provide zero steady state errors of these variables in a very short time.

In case of an interconnected power system having two or more areas connected through tie lines, each area supplies its control area and tie lines allow electric power to flow among the areas. However, a load perturbation in any of the areas affects output frequencies of all the areas as well as the power flow on tie lines. Hence the control system of each area needs information about transient situation in all the other areas to restore the nominal values of area frequencies and tie line powers. [2]

For example, for a two area interconnected power system, this information is taken as $B_i \Delta f_i + \Delta P_{tie}$ (where $i = 1, 2$), where B = tie line frequency bias, f = nominal frequency and P_{tie} = tie line power. This is called as the area control error (ACE) and the same is fed as input to the integral controller of corresponding area. Thus, an AGC scheme for an interconnected power system basically incorporates suitable control system, which can bring the area frequencies and tie line powers back to nominal or very close to nominal values effectively after the load perturbations. [2]

Literature survey shows that many investigations have been carried out to design a robust controller for minimizing the mismatches in frequency and power transfer within the neighboring areas. The controller should provide some degree of robustness under various operating conditions. A set of controller parameters which are

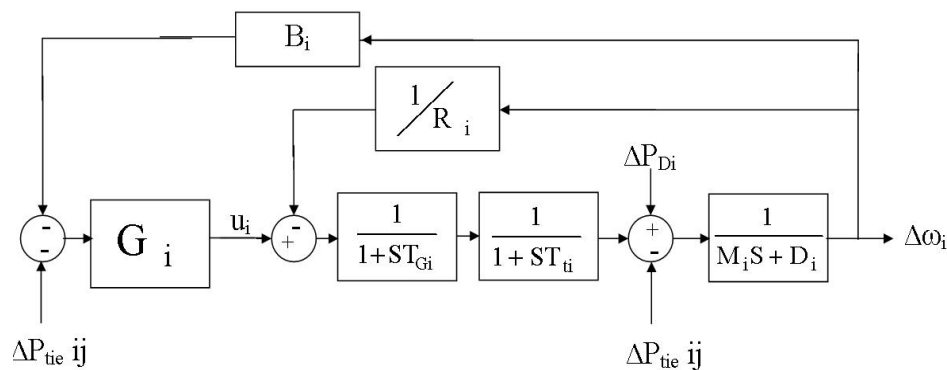
designed to stabilize the system under a certain operating condition may not give satisfactory results for drastic changes in power system operating conditions [3]. A number of articles [13] [14] have been reported on adaptive AGC schemes. An adaptive controller using a proportional integral adaptation to meet the hyper stability condition requirements to take care of the parameter changes of the system was presented by Pan and Liaw [4].

Optimization Techniques constitutes an approach to search for optimized parameters through some form of random search process. Harmony search is a phenomenon mimicking algorithm (also known as meta-heuristic algorithm) inspired by the improvisation process of musicians. In this algorithm, each Musician (decision variable) plays (generates) a notes (values) for finding best harmony (global optimum) all together. Conventional PD, PI, PID controllers does not provide adequate control performance with the effect of governor dead band. Conventional controllers rely on linear design methods and may not provide appropriate regulating signals over a wide range of operating conditions and disturbances. Hence to cover a wide range based on nonlinear conditions, a linguistic approach to develop fuzzy logic controller is employed.

II. Modeling of Power Systems

A two-area electric power system is considered as a test system, the block diagram for each area of interconnected areas is shown in Figure 1 [5].

Figure 1 Block diagram for i^{th} area of system (i^{th} area) [5]



The parameters in Figure 2 are defined as follow [5]:

Δ : Deviation from nominal value

$\Delta\omega_i$ = frequency deviation of the i^{th} area

$M_i=2H$: Constant of inertia of i^{th} area

D_i : Damping constant of i^{th} area

R_i : Gain of speed droop feedback loop of i^{th} area

T_{ti} : Turbine Time constant of i^{th} area

T_{Gi} : Governor Time constant of i^{th} area

G_i : Controller of i^{th} area

ΔP_{Di} : Load change of i^{th} area

u_i : Reference load of i^{th} area

$B_i=(1/R_i)+D_i$: Frequency bias factor of i^{th} area

$\Delta P_{tie ij}$: Inter area tie power interchange from i^{th} area to j^{th} area.

Where:

$i=1, 2, 3, 4$ $j=1, 2, 3, 4$ and $i \neq j$

The inter-area tie power interchange is as (1).

$\Delta P_{tie ij}=(\Delta\omega_i - \Delta\omega_j) \times (T_{ij}/S)$

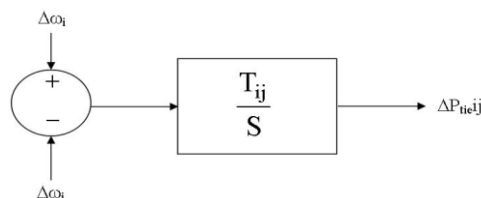
Where:

$T_{ij}=377 \times (1/X_{tie ij})$ (for a 60 Hz system)

$X_{tie ij}$: impedance of transmission line between i and j areas

The $\Delta P_{tie ij}$ block diagram is shown as Figure 2 [5].

Figure 2 Block diagram of inter area tie power ($\Delta P_{tie ij}$) [5]



The necessity of deregulation of the power system is motivated with an increasing number of Independent Power Producers (IPPs) where the power can be sold at a competitive price and performs all functions involved in generation, transmission, distribution according to the retail sales. Hence, a concept of DISCOM participation matrix to is used to understand how the contracts between DISCOMs and GENCOS are implemented. The information flow of the contracts is superimposed on the traditional AGC system.

A. Area Control Error

The frequency deviation of an isolated power system consisting of a single control area is the area control error. The area control error of a control area on an interconnected system is the net interchange minus the biased scheduled net interchange accepted by electric power systems and is in wide use. It is recognized that this is the reverse of the sign of control error generally used in servomechanism and control literature, which defines control error as the reference quantity minus the controlled quantity.

$$ACE = B_i \Delta f_i + \Delta P_{tie} \quad (1)$$

B. Modeling of Two Area Interconnected Power System

A group of one or more generating sources and/or connecting transmission lines operated under common management or supervision to supply load. The following are the nonlinearities that are considered in the basic two-area interconnected system to modify it as an interconnected power system with nonlinearities [4].

C. Reheat Turbine system

Non-reheat turbine system which is called as conventional steam turbine plant, in which the fuel is burned in boilers, that produce high pressure and high temperature steam (usually around 540 to 560 degrees centigrade and 100 to 130 bar (one bar is about the pressure of air at sea level)). The steam is then put through a turbine, which in turn drives the electrical generator [3]. High Pressure (HP), Intermediate Pressure (IP) and Low Pressure (LP) are the different turbine sections. The turbine considered for study in this paper is reheating type. Reheating improves efficiency [5]. The effects of steam chest, reheater and nonlinear characteristics of control valve are considered. The fraction of turbine power generated by intermediate section is assumed as negligible on base value [3].

D. Generation Rate Constraint:

In a power system, the rate of change in the generating power is at a specified maximum limit. For the system considered for study in this work, the generating rate constraints is set by +0.1 or -0.1 by using two limiters in each area within the Automatic Generation Controller to provide the control action within the set limits $\Delta P_g \leq 0.1 \text{ p.u MW/min} = 0.0017 \text{ MW/s}$ [3].

E. Governor Deadband

Governor Deadband is defined as the total magnitude of a sustained speed change within which there is no resulting change. Though the speed governor characteristics are nonlinear they are approximated for linear analysis [6]. The limiting value of governor dead band is 0.06% [7]. One of the effects of governor dead band is to increase the apparent steady state speed regulation R [Concordia et. al]. Turbine – Governor Dead bands are found due to backlash in the linkage connecting the piston to the camshaft [8]. Backlash is the nonlinearity which causes governor dead band and tends to produce continuous sinusoidal oscillations with a natural period of about 2secs [7].

Describing function approach [6] is used to incorporate the governor dead band nonlinearity. The description of the hysteresis type nonlinearities is expressed as

$$Y = F(X, \dot{X}) \quad (1)$$

A necessary assumption is made that the variable x is sufficiently close to a sinusoidal oscillation, that

$$X = A_0 \sin \omega t \quad (2)$$

Where A is the amplitude and ω_0 is the frequency of oscillation are constant ($\omega_0 = \pi$).

As a Backlash nonlinearity is symmetrical about the origin, the Fourier approximated solution is obtained as

$$F(X, \dot{X}) = N_1 X + \frac{N_2}{\omega_0} \dot{X} = (N_1 + \frac{N_2}{\omega_0} \frac{d}{dt}) X = D' B X \quad (3)$$

It has been mentioned from the discussions of [8] the governor dead band is controlled from 0.01%-0.025% which has been achieved experimentally, may lead to unstable operation. For the analysis, in this paper, backlash of approximately 0.01% is chosen.

To solve this, it is a reasonable good to consider the first three terms only. The corresponding coefficients are:

$$F^0 = \frac{1}{2\Pi} \int_0^{2\Pi} F(A \sin w_0 t, A w_0 \cos w_0 t) d(w_0 t)$$

$$N_1 = \frac{1}{\Pi A} \int_0^{2\Pi} F(A \sin w_0 t, A w_0 \cos w_0 t) (\sin w_0 t) d(w_0 t) \quad (4)$$

$$N_2 = \frac{1}{\Pi A} \int_0^{2\Pi} F(A \sin w_0 t, A w_0 \cos w_0 t) (\cos w_0 t) d(w_0 t)$$

As Backlash nonlinearity is symmetrical about the origin, the Fourier is zero. For the analysis in this study, backlash is chosen 0.05%, approximately. The Fourier coefficients are derived as:

$$N_1 = 0.8 \text{ and } N_2 = -0.2$$

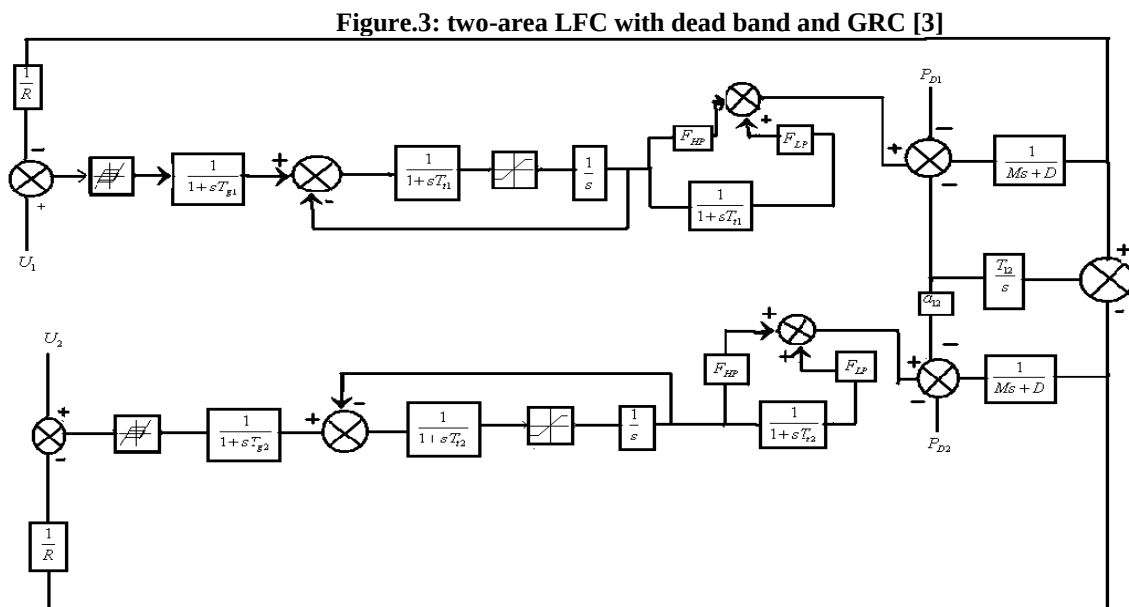
Thus the equation (3) can be written as

$$F(X, \dot{X}) = 0.8X - \frac{0.2}{\Pi} \dot{X} \quad (5)$$

Thus, transfer function of the governor taking dead band into account can be express as:

$$G_{sgi}(s) = \frac{0.8X - \frac{0.2}{\Pi} \dot{X}}{T_{sgi}s} \quad (6)$$

Fig.3 shows the block diagram of two area load frequency control (LFC) with non-linearity's. The system parameters under nominal operating condition and various operating conditions are given in APPENDIX. The dynamic response of the change in frequency (Δf_1) in area1 and change in frequency (Δf_2) in area2 are analyzed and compared under various operating conditions. [3]



III. Design Methodology

AGC in deregulated power systems Deregulated power system consists of generating companies (GENCOs), distribution companies (DISCOMs), transmission companies (TRANSCOs), and independent system operator (ISO). In this environment based on bilateral contracts, DISCOMs have the freedom to contract with any available GENCO in its own area or another control area and these contracts are made under supervision of ISO. To make the visualization of these contracts easier, the concept of a "DISCOM participation matrix (DPM)" will be used. DPM gives the participation of a DISCOM in contract with a GENCO. For example, for large scale power system with m DISCOMs and n GENCOs, the DPM can be given as [9]

$$DPM = \begin{pmatrix} cpf_{11} & \cdots & cpf_{1n} \\ \vdots & \ddots & \vdots \\ cpf_{m1} & \cdots & cpf_{mn} \end{pmatrix}$$

cpf_{ij} is the "contract participation factor", which shows the participation factor of GENCO i in the load following of DISCOM j . the sum of all the entries in a column in this matrix is unity (i.e. Sum of all $Cpf_{ij}=1$ ($i=1$

to n). Whenever a load demanded by a DISCOM changes, it is reflected as a local load in the area to which this DISCOM belongs [9].

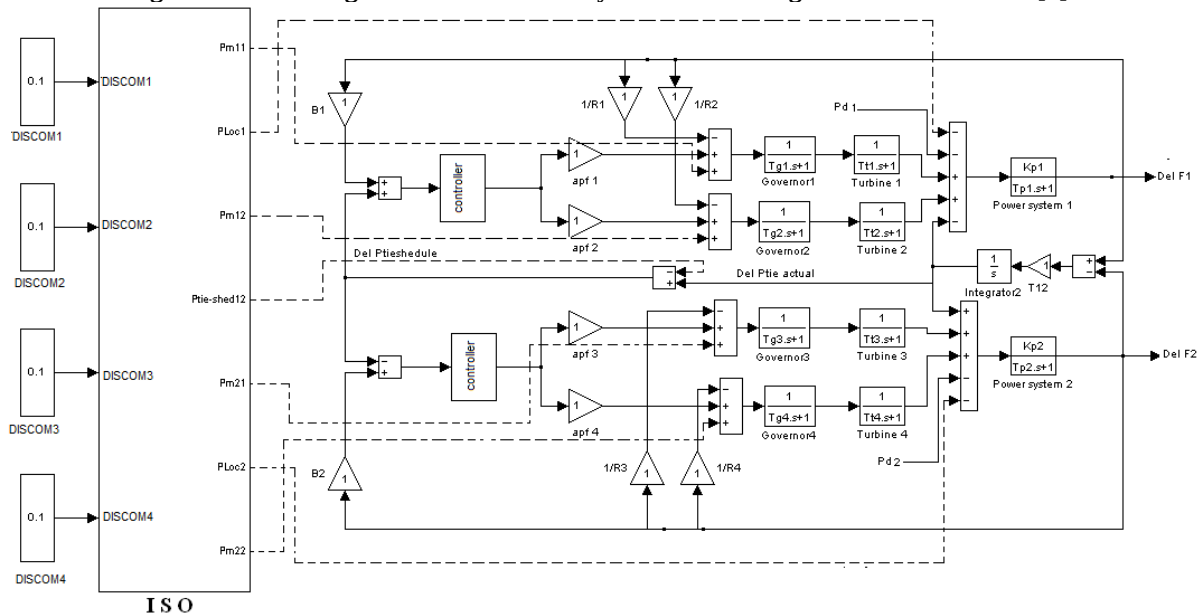
As there are many GENCOs in each area, AGC signal has to be distributed among them according to their participation in the AGC. "ACE Area participation factors (APF)" are the coefficient factors which distributes the ACE among GENCOs. If there are m number of GENCOs then $\sum_{i=1}^m apf_i = 1$. The block diagram for two-area AGC in a deregulated system is shown in Figure.4. Here, we are reformulating the scheduled tie line power which is present in the conventional AGC. The scheduled value of steady state tie line power is given in terms of $\Delta P_{tie\ i-j}$ scheduled [9].

The inputs $\Delta PL_{1, LOC}$ and $\Delta PL_{2, LOC}$ in the closed loop model are part of the power system model, not part of AGC or LFC i.e. load frequency control. The block diagram of two area AGC system in a deregulated environment is shown in Figure 4[9]. The DISCOM Participation Matrix is chosen to be (7)

$$DPM = \begin{bmatrix} 0.5 & 0.25 & 0 & 0.25 \\ 0 & 0 & 1 & 0 \\ 0 & 0.25 & 0 & 0.75 \\ 0. & 0.5 & 0 & 0 \end{bmatrix} \quad (7)$$

$\Delta P_{tie\ i-j}$ scheduled = (Demand of discom's in area 'j' from GENCOs in area 'i')
-(Demand of DISCOMs in area 'i' from GENCOs in area 'j').

Figure.4: Block diagram of 2-area AGC system in an Deregulated Environment [9]



A. Harmony Search Algorithm

Harmony search (HS) algorithm is based on natural musical performance processes that occur when a musician searches for a better state of harmony, such as during jazz improvisation. The engineers seek for a global solution as determined by an objective function, just like the musicians seek to find musically pleasing harmony as determined by an aesthetic [10]. In music improvisation, each player sounds any pitch within the possible range, together making one harmony vector. If all the pitches make a good solution, that experience is stored in each variable's memory, and the possibility to make a good solution is also increased next time. HS algorithm includes a number of optimization operators, such as the harmony memory (HM), the harmony memory size (HMS, number of solution vectors in harmony memory), the harmony memory considering rate (HMCR), and the pitch adjusting rate (PAR). In the HS algorithm, the harmony memory (HM) stores the feasible vectors, which are all in the feasible space. The harmony memory size determines how many vectors it stores. A new vector is generated by selecting the components of different vectors randomly in the harmony memory. In order to explain the Harmony Search in more detail, let us first idealize the improvisation process by a skilled musician. When a musician is improvising, he or she has three possible choices: (1) play any famous piece of music (a series of pitches in harmony) exactly from his or her memory; (2) play something similar to a known piece (thus adjusting the pitch slightly); or (3) compose new or random

notes. Zong Woo Geem et al. formalized these three options into quantitative optimization process in 2001, and the three corresponding components become: usage of harmony memory, pitch adjusting, and randomization. Similarly, when each decision variable chooses one value in the HS algorithm, it follows any one of three rules: (1) choosing any one value from HS memory (defined as memory considerations), (2) choosing an adjacent value of one value from the HS memory (defined as pitch adjustments), and (3) choosing totally random value from the possible value range (defined as randomization). The three rules in HS algorithm are effectively directed using two parameters, i.e., harmony memory considering rate (HMCR) and pitch adjusting rate (PAR). The steps in the procedure of harmony search are as follows [5]:

- Step1. Initialize the problem and algorithm parameters.
- Step2. Initialize the harmony memory (HM).
- Step3. Improvise a new harmony from the HM.
- Step4. Update the HM.
- Step5. Repeat Steps 3 and 4 until the termination criterion is satisfied.

B. Initialize the Problem and Algorithm Parameters [5]

Specify the optimization problem as Minimize $f(x)$, Subject to $x_i \in X_i$ Where $i=1,2,\dots,N$, Where $f(x)$ is an objective function, x is set of decision variables x_i , N is the number of decision variables and X_i represents the possible range of values for each decision variables. The HS algorithm parameters to be initialized are as follows:

Harmony memory size (HMS): this indicates the number of solution vectors in the harmony memory, HMCR, PAR, Number of improvisations (NI) or stopping criteria.

C. The Algorithm has the Following Steps [11,12]

Step 1: Generate random vectors $(x', \dots, x^{hms})$ as many as hms (harmony memory size), then store them in harmony memory (HM).

$$HM = \begin{bmatrix} x_1^1 & \cdots & x_n^1 & | & f(x^1) \\ \vdots & & \vdots & | & \\ x_1^{hms} & \cdots & x_n^{hms} & | & f(x^{hms}) \end{bmatrix} \quad (8)$$

Step 2: Generate a new vector x' . For each component x'_i ,

- with probability hmcr (harmony memory considering rate; $0 \leq hmcr \leq 1$), pick the stored value from HM: $x'_i \leftarrow x_i^{\text{int}(u(0,1)*hms)+1}$
- With probability $1-hmcr$, pick a random value within the allowed range.

Step 3: Perform additional work if the value in Step 2 came from HM.

- with probability par (pitch adjusting rate; $0 \leq par \leq 1$), change x'_i by a small amount: $x'_i \leftarrow x'_i + \delta$ or $x'_i \leftarrow x'_i - \delta$ for discrete variable; or $x'_i \leftarrow x'_i + f \cdot u(-1,1)$ for continuous variable.
- With probability $1-par$, do nothing.

Step 4: If x' is better than the worst vector X^{worst} in HM, replace X^{worst} with x' .

Step 5: Repeat from Step 2 to Step 4 until termination criterion (e.g. maximum iterations) is satisfied.

The parameters of the algorithm are

- hms = the size of the harmony memory. It generally varies from 1 to 100. (typical value = 30)
- hmcr = the rate of choosing a value from the harmony memory. It generally varies from 0.7 to 0.99. (typical value = 0.9)
- par = the rate of choosing a neighboring value. It generally varies from 0.1 to 0.5. (typical value = 0.3)
- δ = the amount between two neighboring values in discrete candidate set.
- fw (fret width, formerly bandwidth) = the amount of maximum change in pitch adjustment. This can be $(0.01 \times \text{allowed range})$ to $(0.001 \times \text{allowed range})$.

It is possible to vary the parameter values as the search progresses, which gives an effect similar to stimulate annealing.

D. Optimal Parameter Tuning Using Harmony Search Algorithm

Fuzzy PID Controller (FPID):

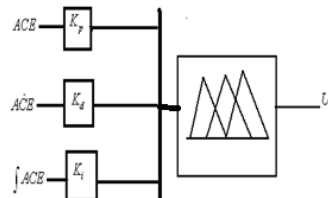
In proposed design, two variables $ACE, \int ACE$ are used as input signals. The coefficients K_p, K_i, K_d which are called scaling factors, transform the scaled real values to required value in decision limit. The output

signal coefficient K_u is injected to the summing point. The range of each Fuzzy variable is normalized between -1 to +1 with 3 membership functions. The interface mechanism gives the set of decision (3X3X3=27) rules. These rules relate all possible combinations of inputs to outputs.

E. Tuning of FPID parameters

Figure.5 shows the block diagram of Fuzzy Logic Proportional plus Integral Derivative(FPID) controller. K_p, K_d, K_i are the two input gains to the Fuzzy PID controller, K_u is the output gain, are tuned using Harmony Search Algorithm. The performance Index for the Tuning of optimized parameters of FPID controller is chosen as Integral Time Square Error. The Optimal parameters are obtained by minimizing the objective function in eq (9)

Figure: 5 block diagram of FPID controller



The parameters of the proposed PID controllers are tuned using harmony search algorithm. These K parameters are obtained based on the Harmony search algorithm optimization method. The PID controller has three parameters denoted by K_p, K_i and K_D and for each area there is a PID controller. [5]

Here these controllers are substituted by PID controllers and the optimum. In fact, the performance index is the Integral of the Time multiplied Absolute value of the Error (ITAE) [3].

$$ITAE = \int_0^t t * e^2(t) dt \quad (9)$$

The parameter "t" in ITAE is the simulation time. It is clear to understand that the controller with lower ITAE is better than the other controllers. To compute the optimum parameter values, a 10 % step change in ΔP_D is assumed and the performance index is minimized using Harmony search algorithm. In order to acquire better performance, the Harmony search algorithm parameters have been considered as follow [5].

Number of decision variables (N): 3

Harmony memory size (HMS): 48

Number of improvisations (NI): 100

HMCR: 0.9

Subjective constraints are [13]:

$$0.6 * k_{cr} > 0; (\because k_p = 0.6 * k_{cr})$$

$$0.5 * p_{cr} > 0;$$

$$0.125 * p_{cr} > 0;$$

$$\text{where } k_{cr} > 0, p_{cr} > 0;$$

$$k_i = k_p / T_i;$$

$$k_d = k_p * T_d;$$

IV. Results and Discussion

Comparative step response analysis based on percent overshoot, percent undershoot, and settling time for frequency deviation in area1 when similar controllers are incorporated in each area under different operating conditions is analyzed in this paper. The performance of FPID controller under various operating conditions is tabulated in TableIII. for step load disturbance of 1% in area1. The tabulated results of performance analysis shows that the settling time is improved under all the operating conditions when FPID controller is incorporated. The percent overshoot and the percent undershoot with FPID controller is minimized to negligible percents. In this paper, the aim is to minimize the steady state error, percent overshoot, percent undershoot and hence to improve the dynamic stability of the Restructured two area power system. With the above comparisons FPID controllers provide robustness to the system. Figure.6-14 shows the frequency deviations in area1 and area2 under various operating points. It can be observed that in each operating point the performance of the system can be improved in percent overshoot and percent undershoot with Fuzzy PID (FPID) controller.

Table II: optimal parameters of HS-FPID for different areas

Areas	K_p	K_i	K_d
Area1	4.9925	5.9975	2.0125
Area2	4.865	5.725	1.975

Figure 6 frequency deviation in area1 under normal load

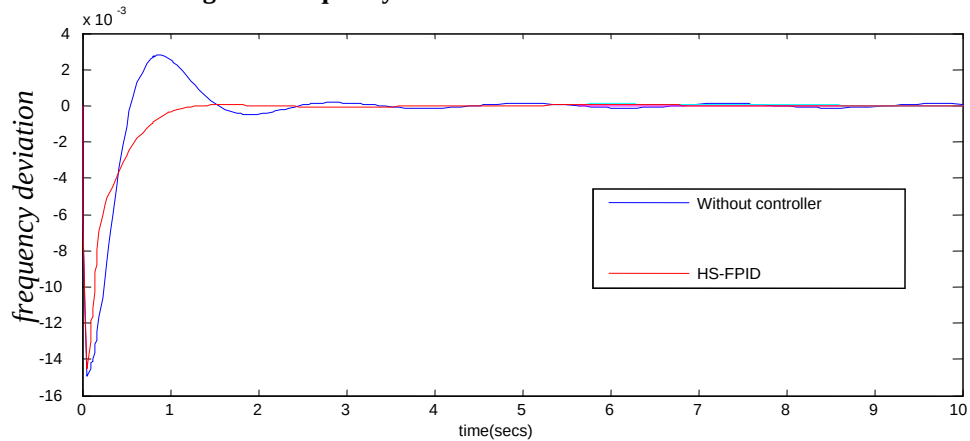


Figure 7 frequency deviation in area2 under normal load

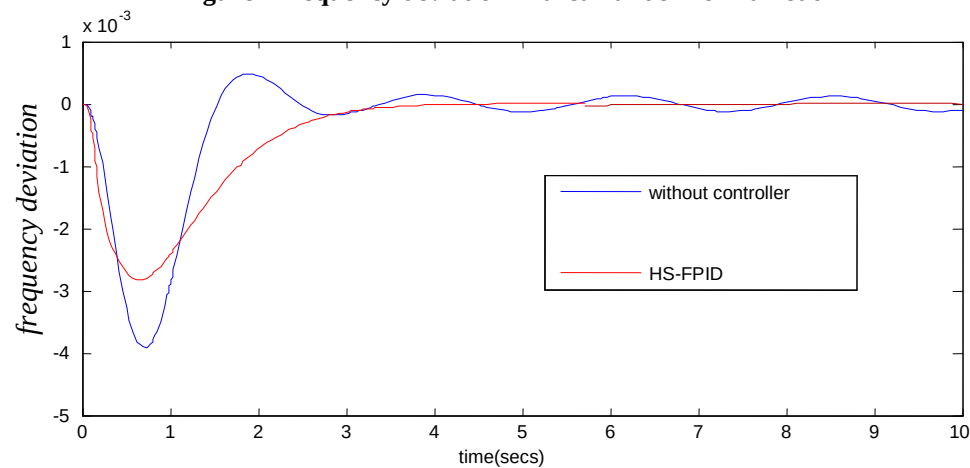


Figure 8 frequency deviation in area1 under 40% overloaded

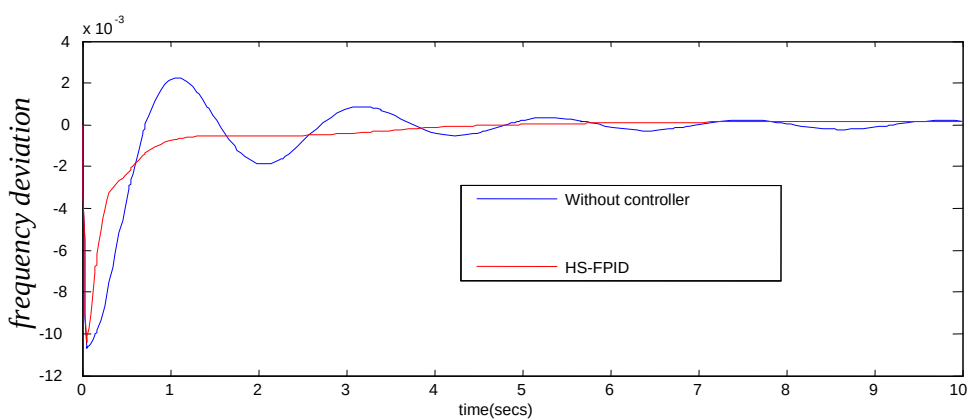


Figure 9 frequency deviation in area2 under 40% overloaded

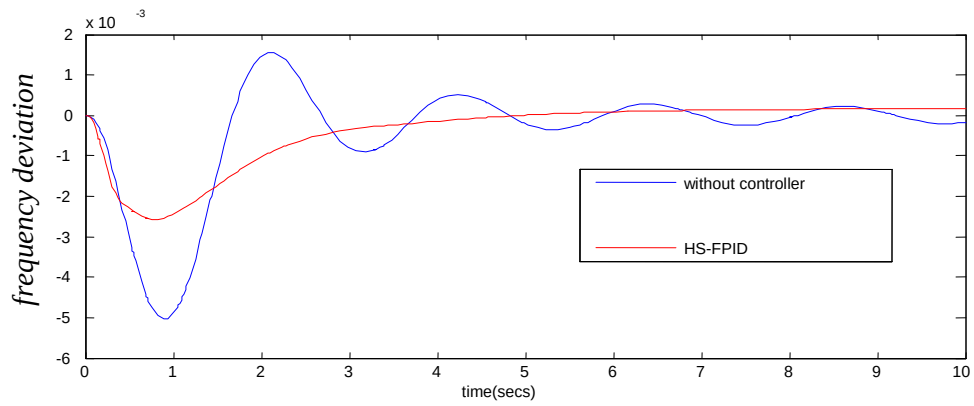


Figure 10 frequency deviation in area1 under 10% over loaded

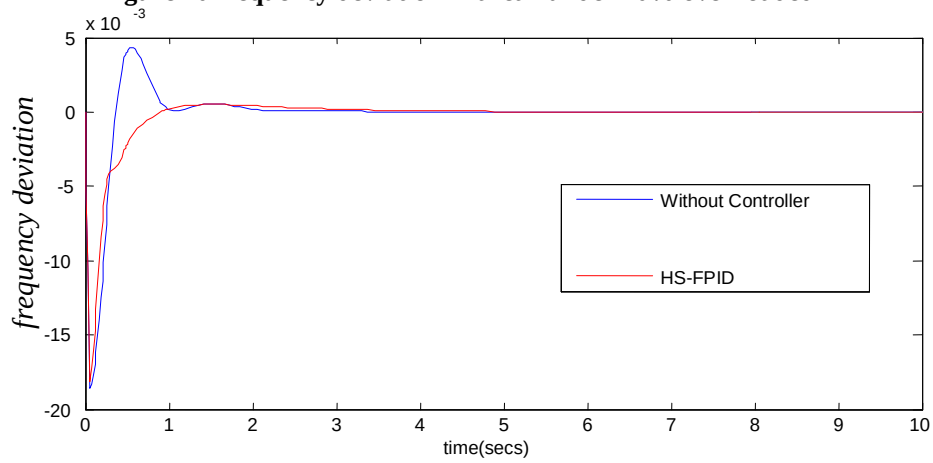


Figure 11 frequency deviation in area2 under 10% over loaded

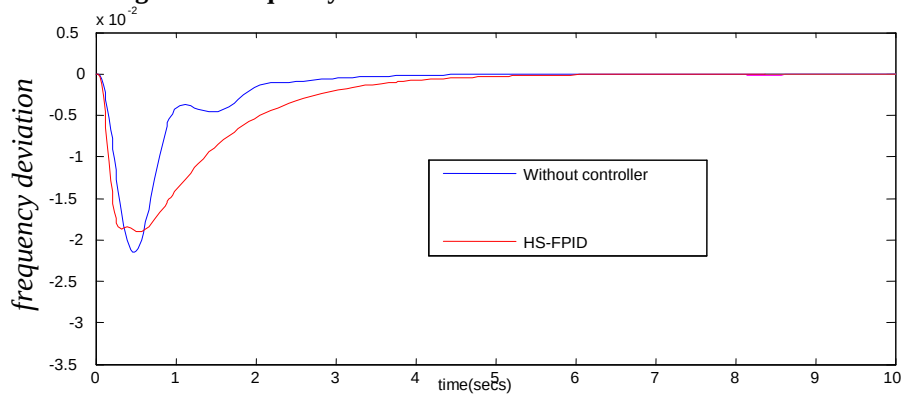
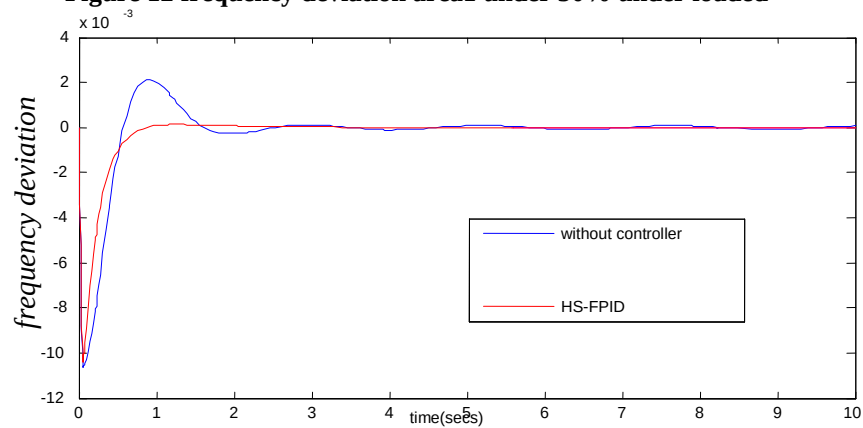


Figure 12 frequency deviation area1 under 30% under loaded



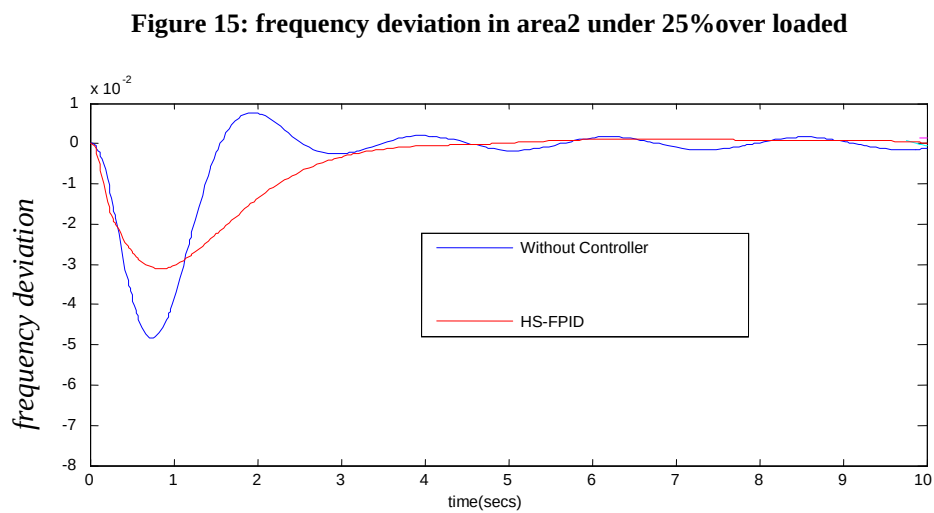
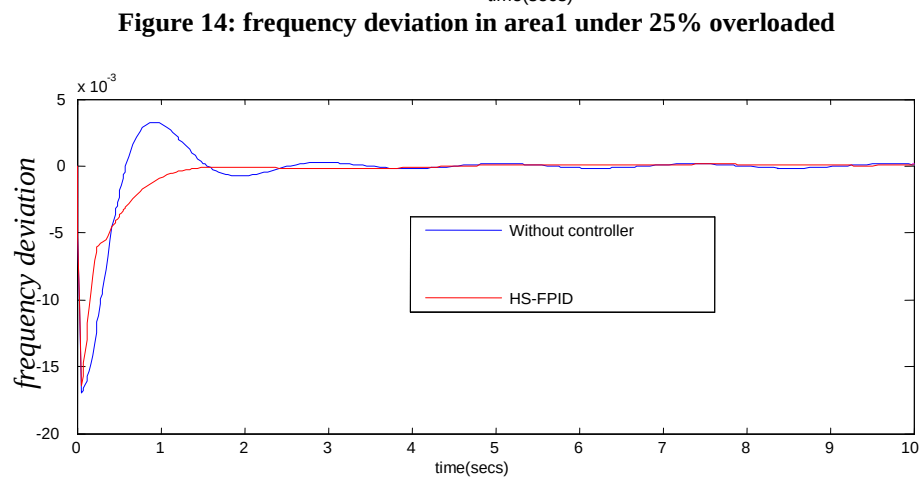
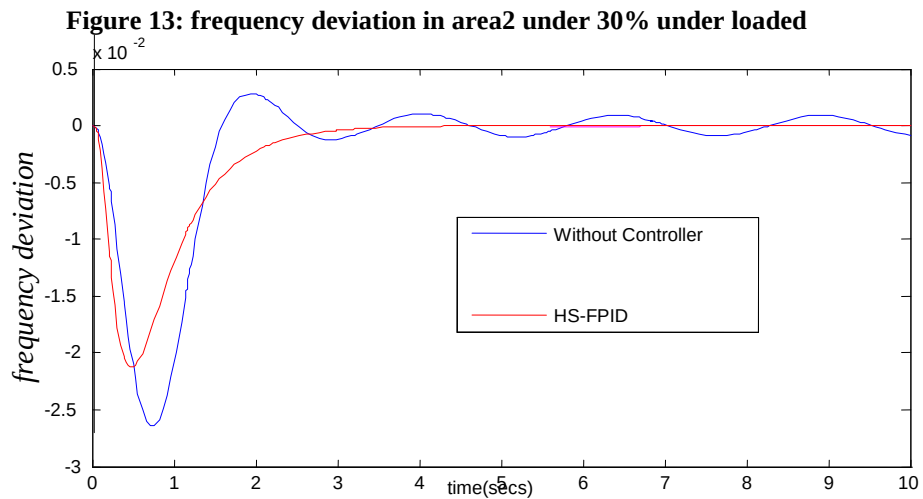


Table.III: Performance of HSFPID

Operating Condition	HS FPID	
	%Over-shoot	%Under-shoot
Normal loading	-----	1.45
40% over loading	-----	1.03
10% Over loading	0.05	1.81
30% Under loading	0.01	1.04
25% Over loading	-----	1.64

V. Conclusions

The proposed Controller is employed with a two area interconnected reheat thermal power system with GRC and Deadband in deregulated environment under various operating conditions. The results depict the effective performance of HS-FPID and the proposed controller guaranteed the effective performance of the proposed controller under all operating conditions.

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APPENDIX:

Nominal Operating condition:

$$T_{T1} = 0.03, T_{G1} = 0.08,$$

$$T_{P1} = 20, R_1 = 2.4, K_{P1} = 120,$$

$$T_{12} = 0.545, B_1 = 0.425,$$

$$K_1 = 1, a_{12} = -1$$

Operating point 1: Nominal condition, **Operating point 2:** 40% overloading on nominal point.

Operating point 3: 10% overloading on nominal point, **Operating point 4:** 30% under loading on nominal point, **Operating point 5:** 25% overloading on nominal point.