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MULTI STAGE FUZZY PID LOAD FREQUENCY CONTROLLER IN A RESTRUCTURED POWER SYSTEM

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In this paper, a multi stage fuzzy Proportional-Integral-Derivative (PID) type controller is proposed to solve the Load Frequency Control (LFC) problem in a restructured power system that operates under deregulation based on the bilateral policy scheme. In each control area, the effects of the possible contracts are treated as a set of new input signal in a modified traditional dynamical model. The multi stage controller uses the fuzzy switch to blend a Proportional-Derivative (PD) fuzzy logic controller with an integral fuzzy logic input. The proposed controller operates on fuzzy values passing the consequence of a prior stage on to the next stage as a fact. The salient advantage of this strategy is its high insensitivity to large load changes and disturbances in the presence of plant parameter variations and system nonlinearities. This newly developed strategy leads to a flexible controller with a simple structure that is easy to implement and therefore it can be useful for the real world power system. The proposed method is tested on a three-area power system with different contracted scenarios under various operating conditions. The results of the proposed controller are compared with the classical fuzzy PID type controller and mixed H_2/H_∞ controller through some performance indices to illustrate its robust performance.

K e y w o r d s: LFC, fuzzy PID type controller, restructured power system, fuzzy switch, PID, power system control

1 INTRODUCTION

The dynamic behaviour of many industrial plants is heavily influenced by disturbances and, in particular, by changes in the operating point. This is typically the case for the restructured power systems. Load Frequency Control (LFC) is a very important issue in power system operation and control for supplying sufficient and reliable electric power with good quality. The main goal of the LFC is to maintain zero steady state errors for frequency deviation and good tracking load demands in a multi-area restructured power system. In addition, the power system should fulfil the requested dispatch conditions. A lot of studies have been made in the last two decades about the LFC in interconnected power systems [1–13].

The real world power system contains different kinds of uncertainties due to load variations, system modelling errors and change of the power system structure. As a result, a fixed controller based on the classical theories is certainly not suitable for the LFC problem. Consequently, it is required that a flexible controller be developed. The conventional control strategy for the LFC problem is to take the integral of the area control error as the control signal. An integral controller provides zero steady state deviation but it exhibits poor dynamic performance [2–3]. To improve the transient response, various control strategy, such as linear feedback, optimal control and variable structure control have been proposed [4–7]. However, these methods need some information for the system states, which are very difficult to know completely. There have been continuing efforts in designing LFC with better performance to cope with the plant parameter changes, using various adaptive neural networks and robust methods [8–13]. The proposed methods show good dynamical responses, but robustness in the presence of model dynamical uncertainties and system nonlinearities were not considered. Also, some of them suggest complex state feedback or high order dynamical controllers, which are not practical for industry practices.

Research on the LFC problem shows that, the fuzzy Proportional-Integral (PI) controller is simpler and more applicable to remove the steady state error [14–17]. The fuzzy PI controller is known to give poor performance in the system transient response. In view of this, some authors proposed fuzzy Proportional-Integral-Derivative (PID) methods to improve the performance of the fuzzy PI controller [15–17]. It should be pointed out that it requires a three-dimensional rule base. This problem makes the design process is more difficult. In order to overcome this drawback and focus on the separation PD part from the integral part, this paper presents a Multi Stage Fuzzy PID (MSFPID) controller with fuzzy switch. This is a form of behaviour based control where the PD controller becomes active when certain conditions are met. The resulting structure is a controller using two- dimensional inference engines (rule base) to reasonably perform the task of a three-dimensional controller. The proposed method requires fewer resources to operate and its role in the system response is more apparent, *ie* it is easier to understand the effect of a two-dimensional controller than a three-dimensional one [18]. This newly developed control strategy combines fuzzy PD controller and integral controller with a fuzzy switch. The fuzzy PD stage is employed to penalize fast change and large overshoots in the control input due to corresponding practical constraints. The Integral stage is used in order to get disturbance rejection and zero steady state error.

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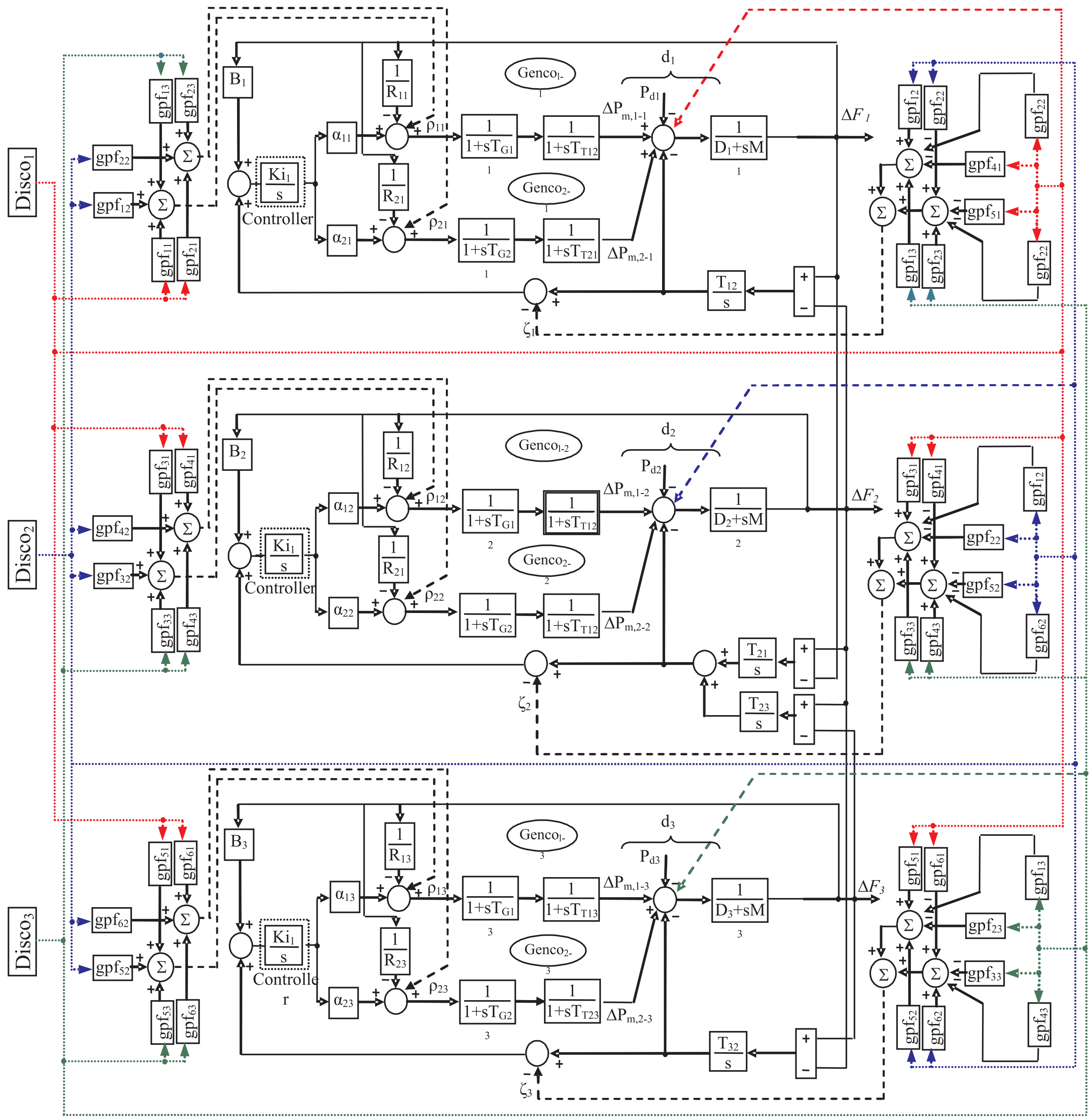

Fig. 1. Modified control area in restructured environment.

The proposed control has simple structure and dose not require an accurate model of the plant. Thus, its construction and implementation are fairly easy and can be useful for the real world complex power system. The proposed method is applied to a three-area restructured power system as a test system. The results of the proposed MSFPID controller are compared with the Classical Fuzzy PID (CFPID) controller [15] and mixed H_2/H_∞ controller [8] through some performance indices in the presence of large parametric uncertainties and system nonlinearities under various area load changes. The performance indices have been chosen as the Integral of the Time multiplied Absolute value of the Error (ITAE), the Integral of the Time multiplied Square of the Error (ITSE), Integral of the Square of the Error (ISE) and Figure of Demerit (FD). The simulation results show that not only the proposed controller can guarantee the robust performance for a wide range of load changes and parametric uncertainties even in the presence of Generation Rate Constraints (GRC), but also the system performance such as: ITAE, ITSE, ISE and FD indices are very better than the CFPID and mixed H_2/H_∞ controllers.

2 RESTRUCTURED POWER SYSTEM MODEL

In the restructured power systems, the Vertically Integrated Utility (VIU) no longer exists. However, the common LFC goals, *ie* restoring the frequency and the net interchanges to their desired values for each control area, still remain. Generalized dynamical for the LFC scheme

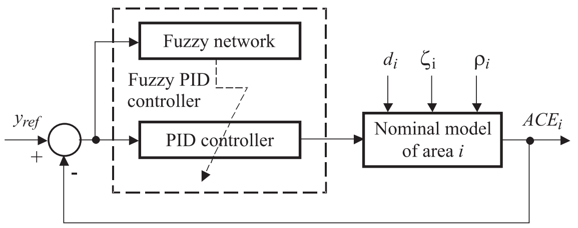

Fig. 2. The proposed FPID controller design problem.

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

$$AGPM = \begin{bmatrix} AGPM_{11} & \dots & AGPM_{1N} \\ \vdots & \ddots & \vdots \\ AGPM_{N1} & \dots & AGPM_{NN} \end{bmatrix} \tag{1}$$

where,

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

for $i,j = 1,\dots,N$, $s_i = \sum_{k=1}^{i-1} n_i$, $z_j = \sum_{k=1}^{j-1} m_j$, $s_1 = z_1 = 0$.

In the above, n_i and m_i are the number of GENCOs and DISCOs in area i and gpf_{ij} refer to 'generation participation factor' and shows the participation factor GENCO i in total load following requirement of DISCO j based on the possible contract. The Sum of all entries in each column of AGPM is unity.

To illustrate the effectiveness of the modelling strategy and proposed control design, a three control area power system is considered as a test system. It is assumed that each control area includes two GENCOs and a DISCO. Block diagram of the generalized LFC scheme for a three-area restructured power system is shown in Fig. 1. The nomenclature used and power system parameters are given in Appendices A and B, respectively.

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

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

$$\eta_i = \sum_{\substack{j=1 \\ j\neq i}} T_{ij}\Delta f_j\,, \tag{3}$$

$$\zeta_i = \Delta P_{tie,i,sch} = \sum_{\substack{k=1 \\ k\neq i}}^{N} \Delta P_{tie,ik,sch} \tag{4}$$

$$\Delta P_{tie,ik,sch} = \sum_{j=1}^{n_l}\sum_{i=1}^{m_k} apf_{(s_i+j)(z_k+i)}\Delta P_{L(z_k+i)-5} - \sum_{i=1}^{n_k}\sum_{j=1}^{m_i} apf_{(s_k+i)(z_i+j)}\Delta P_{L(z_l+j)-i}\,, \tag{5}$$

$$\Delta P_{tie,i-error} = \Delta P_{tie,i-actual} - \zeta_i\,, \tag{6}$$

$$\rho_i = [\rho_{1i}\ \dots\ \rho_{ki}\ \dots\ \rho_{n_i i}]\,,\ \rho_{ki} = = \sum_{j=1}^{N}\sum_{t=1}^{m_j} gpf_{(s_i+k)(z_j+t)}\Delta P_{Lt-i}\,, \tag{7}$$

$$\Delta P_{m,k-i} = \rho_{ki} + apf_{ki}\Delta P_{di}\,,\ k = 1,2,\dots,n_i\,. \tag{8}$$

3 FUZZY BASED CONTROLLER DESIGN

Fuzzy set theory and fuzzy logic establish the rules of a nonlinear mapping. The use of fuzzy sets provides a basis for a systematic way for the application of uncertain and indefinite models. Fuzzy control is based on a logical system called fuzzy logic is much closer in spirit to human thinking and natural language than classical logical systems.

Nowadays fuzzy logic is used in almost all sectors of industry and science. One of them is power system control. Because of the complexity and multi-variable conditions of the power system, conventional control methods may not give satisfactory solutions. On the other hand, their robustness and reliability make fuzzy controllers useful for solving a wide range of control problems in the power systems. In general, the application of fuzzy logic to PID control design can be classified in two major categories according to the way of their construction [16]:

1. A typical LFC is constructed as a set of heuristic control rules, and the control signal is directly deduced from the knowledge base.
2. The gains of the conventional PID controller are tuned on-line in terms of the knowledge based and fuzzy inference, and then, the conventional PID controller generates the control signal.

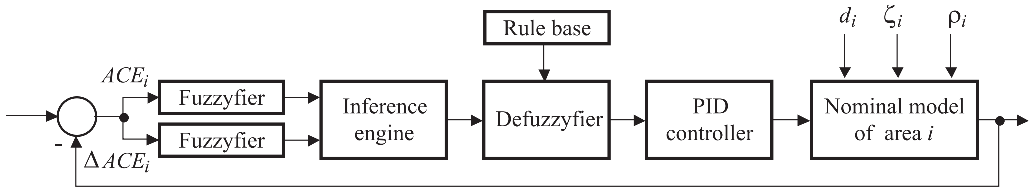

Fig. 3. The scheme of Fuzzy Network.

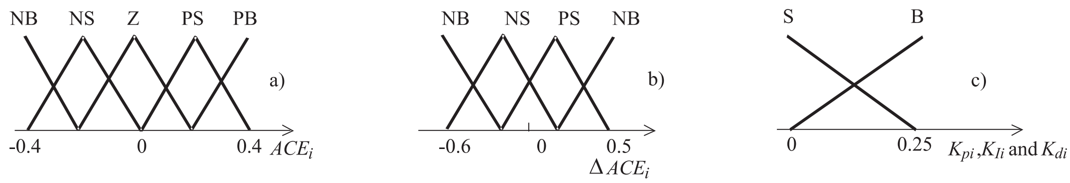

Fig. 4. a) Membership for ACE_i, b) Membership for ΔACE_i, c) Membership for K_{Ii}, K_{Pi} and K_{di}

Table 1. Rule Table for KIi.

	NB	NS	PS	PB
NB	S	S	S	S
NS	S	B	B	S
Z	B	B	B	B
PS	S	B	B	S
PB	S	S	S	S

Table 2. Rule Table for KPi.

	NB	NS	PS	PB
NB	S	S	S	S
NS	S	B	B	S
Z	B	B	B	B
PS	S	B	B	S
PB	S	S	S	S

Table 3. Rule Table for Kdi.

	NB	NS	PS	PB
NB	B	B	B	B
NS	B	S	S	B
Z	S	S	S	S
PS	B	S	S	B
PB	B	B	B	B

Figure 2 shows the block diagram of fuzzy type controller to solve the LFC problem for each control area (Fig. 1).

In the design of fuzzy logic controller, there are five parts of the fuzzy inference process:

1. Fuzzification of the input variables.
2. Application of the fuzzy operator (AND or OR) in the antecedent.
3. Implication from the antecedent to the consequent.
4. Aggregation of the consequents across the rules.
5. Defuzzification.

3.1 Classical Fuzzy PID Controller

According to the control methodology as given in Ref. [15] a fuzzy PID controller for each of three areas is designed. The proposed controller is a two-level controller. The first level is fuzzy network and the second level is PID controller. The structure of the classical FPID controller is shown in Fig. 3, where the PID controller gains is tuned online for each of the control areas.

The controller block is formed by fuzzification of Area Control Error (ACE_i), the interface mechanism and defuzzification. Therefor U_i is a control signal that applies to governor set point in each area. By taking ACE_i as the system output, the control vector for a conventional PID controller is given by:

$$u_i = K_{Pi} ACE_i(t) + K_{Ii}\int_0^t ACE_i(t)\mathrm{d}t + K_{di} A\dot{C}E(t)\,. \quad (9)$$

In this strategy, the conventional controller for LFC scheme (Fig. 1) is replaced by a fuzzy PID type controller. The gains K_{Pi}, K_{Ii} and K_{di} in (9) are tuned on-line in terms of the knowledge base and fuzzy inference, and then, the conventional PID controller generates the control signal. The motivation of using the fuzzy logic for tuning gains of PID controllers is to take large parametric uncertainties, system nonlinearities and to minimize the area load disturbances.

Fuzzy logic shows experience and preference through its membership functions. These functions have different shapes depending on the system expert's experience. The membership function sets for ACE_i, ΔACE_i, K_{Ii}, K_{di} and K_{pi} are shown in Fig. 4. The appropriate rules for the proposed control strategy are given in Tables 1, 2 and 3.

This control methodology for the LFC problem shows good dynamical responses with robustness in the presence of dynamical uncertainties and system nonlinearities. From Fig. 3, It should be pointed out that fuzzy PID controller normally requires a three-dimensional rule base. This is difficult to obtain since three-dimensional information is usually beyond the sensing capability of a human expert and it makes the design process more complex.

3.2 Multi Stage Fuzzy PID Controller

Multi stage fuzzy PID controller with fuzzy switch is a kind of controller where the PD controller becomes active when certain conditions are met. The resulting structure is a controller using two-dimensional inference engines (rule base) to reasonably perform the task of a

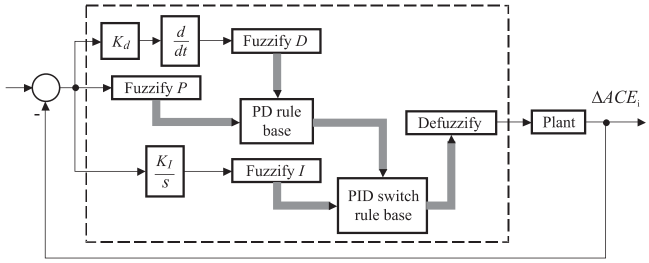

Fig. 5. The proposed multi stage fuzzy PID controller.

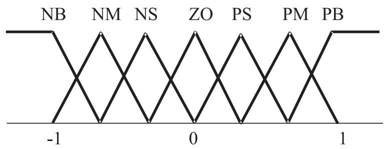

Fig. 6. Symmetric Fuzzy Partition.

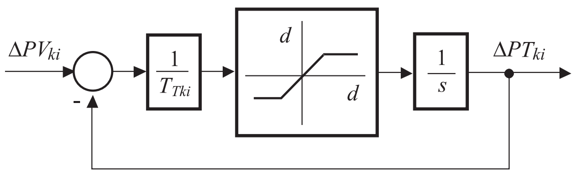

Fig. 7. Nonlinear turbine model with GRC.

Table 4. PD rule base.

e \ Δe	NB	NM	NS	ZO	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZO
NM	NB	NB	NB	NM	NS	ZO	PS
NS	NB	NB	NM	NS	ZO	PS	PM
ZO	NB	NM	NS	ZO	PS	PM	PB
PS	NM	NS	ZO	PS	PM	PB	PB
PM	NS	ZO	PS	PM	PB	PB	PB
PB	ZO	PS	PM	PB	PB	PB	PB

Table 5. PID switch rule base.

$\int e$ \ PD Values	NB	NM	NS	ZO	PS	PM	PB
NB	NB	NM	NS	NB	PS	PM	PB
NM	NB	NM	NS	NM	PS	PM	PB
NS	NB	NM	NS	NS	PS	PM	PB
ZO	NB	NM	NS	ZO	PS	PM	PB
PS	NB	NM	NS	PS	PS	PM	PB
PM	NB	NM	NS	PM	PS	PM	PB
PB	NB	NM	NS	PB	PS	PM	PB

three-dimensional controller. The proposed method requires fewer resources to operate and its role in the system response is more apparent, *ie* it is easier to understand the effect of a two-dimensional controller than a three-dimensional one. This controller strategy combines fuzzy PD controller and integral controller with a fuzzy switch. The fuzzy PD stage is employed to penalize fast change and large overshoots in the control input due to corresponding practical constraints. The integral stage is used in order to get disturbance rejection and zero steady state error.

The structure for the MSFPID controller follows directly from a classical PID controller is shown in Fig. 5. In the multi stage structure, input values are converted to truth-value vectors and applied to their respective rule base. The output truth-value vectors are not defuzzified to crisp value as with a single stage fuzzy logic controller but are passed onto the next stage as a truth value vector input. The darkened lines in Fig. 5 indicate truth value vectors.

In this effort, all membership functions are defined as triangular partitions with seven segments from -1 to 1. Zero (ZO) is the centre membership function which is centred at zero. The partitions are also symmetric about the ZO membership function as shown in Fig. 6. The remaining parts of the partition are Negative Big (NB), Negative Medium (NM), Negative Small (NS), Positive Small (PS), Positive Medium (PM), Positive Big (PB).

There are two rule bases used in the MSFPID. The first is called the PD rule bases as it operates on truth vectors form the error (e) and change in error (Δe) inputs. A typical PD rule base for the fuzzy logic controller is given in Table 4. This rule base responds to a negative input from either error (e) or change in error (Δe) with a negative value thus driving the system to ward the commanded value. Table 5 shows a PID switch rule base. This rule base is designed to pass through the PD input if the PD input is not in zero fuzzy set. If the PD input is in the zero fuzzy set, then the PID switch rule base passes the integral error values ($\int e$). This rule base operates as the behaviour switch, giving control to PD feedback when the system is in motion and reverting to integral feedback to remove steady state error when the system is no longer moving. The operation used to determine the consequence value at the intersection of two input fuzzy value is given as:

$$c_{i,j} = \prod (a_i * b_j)\,,\ i,j = 1,2,\dots,N_m\,. \tag{10}$$

Where a_i is the membership value of i^{th} fuzzy set for a given e input, and b_j is likewise for a δe input. The operator used to determine the membership value of the k^{th} consequence set is:

$$C_k = \sum C_{i,j}\,,\ i,j = 1,2,\dots,N_m\,. \tag{11}$$

The defuzzification uses the weighted average method where C_k is the peak point of the k^{th} output fuzzy membership function.

$$d = \sum C_k * c_k \Big/ \sum C_k\,,\ k = 1,\dots,N\,.$$

(sets in output point) (12)

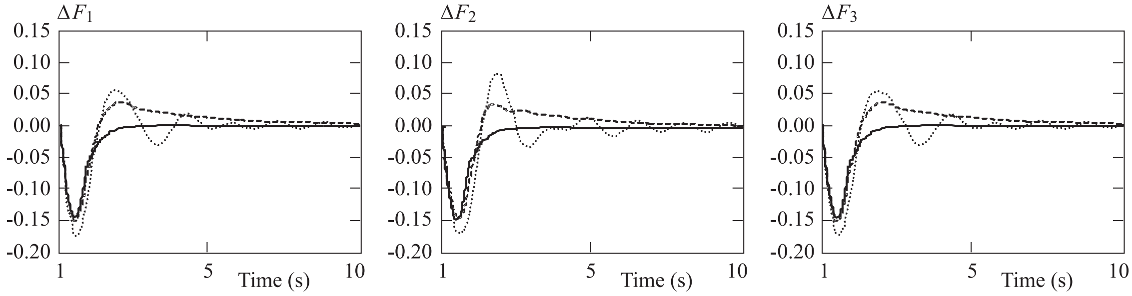

Fig. 8. Frequency deviation of three areas. Solid (MFPID), Dashed (Mixed H_2/H_∞), Dotted (FPID).

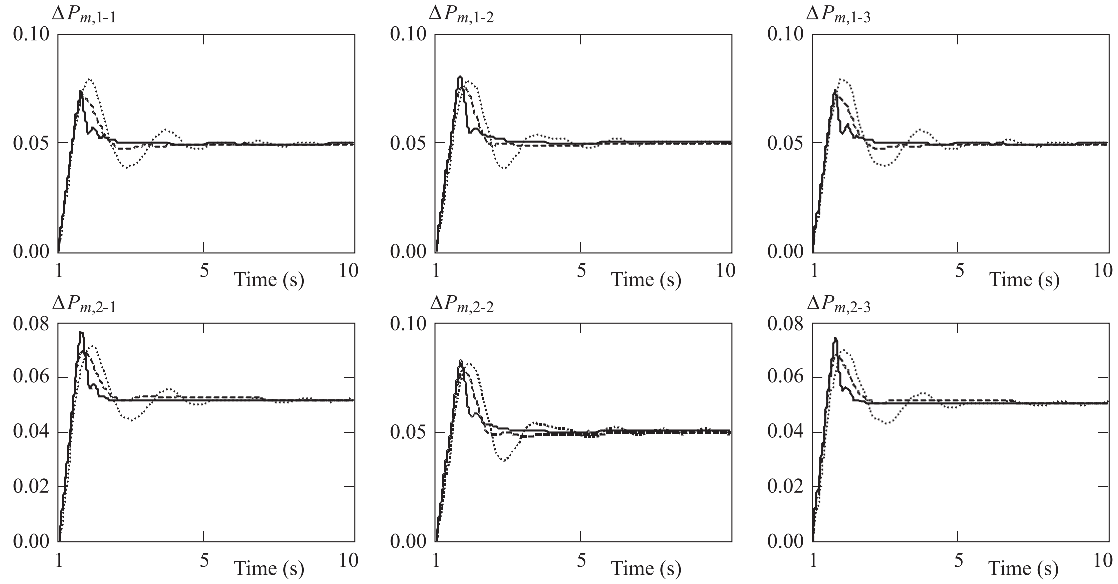

Fig. 9. GENCOs powerchange. Solid (MFPID), Dashed (Mixed H_2/H_∞), Dotted (FPID).

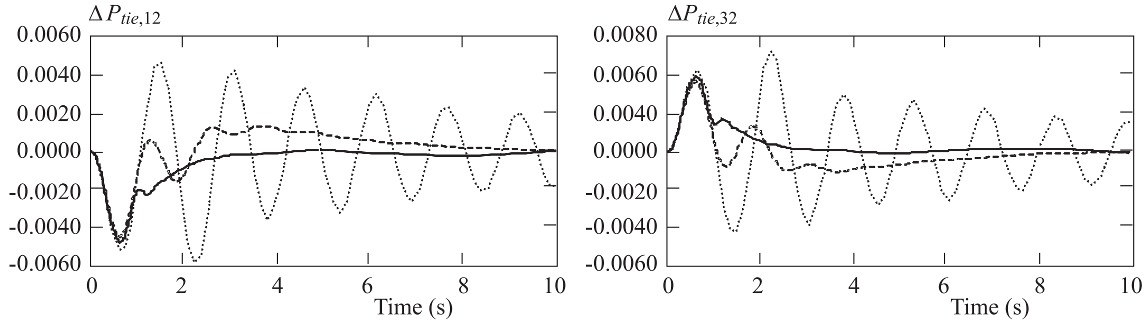

Fig. 10. Deviation of tie line power flow. Solid (MFPID), Dashed (Mixed H_2/H_∞), Dotted (FPID).

4 SIMULATION RESULTS

In the simulation study, the linear model of turbine $\Delta PV_{ki}/\Delta PT_{ki}$ in Fig. 1 is replaced by a nonlinear model of Fig. 7 with ± 0.1. This is to take GRC into account, *ie* the practical limit on the rate of the change in the generating power of each GENCO.

The proposed MSFPID controller is applied for each control area of the restructured power system as given in Sec. 2. To illustrate robustness of the proposed control strategy against parametric uncertainties and contract variations, simulations are carried out for three scenarios of possible contracts under the following operating conditions and large load demands.

Case A: With nominal parameters for three areas.

Case B: Increasing parameters of each area simultaneously by 25 % from nominal values.

Case C: Decreasing parameters of each area simultaneously by 25 % from nominal values.

Performance of the proposed MSFPID controllers is compared with the CFPID and mixed H_2/H_∞ controllers. The syntheses methodologies of the LFC problem as a mixed H_2/H_∞ controller optimization problem in detail is given in *Ref* [8] which addressed by the Linear

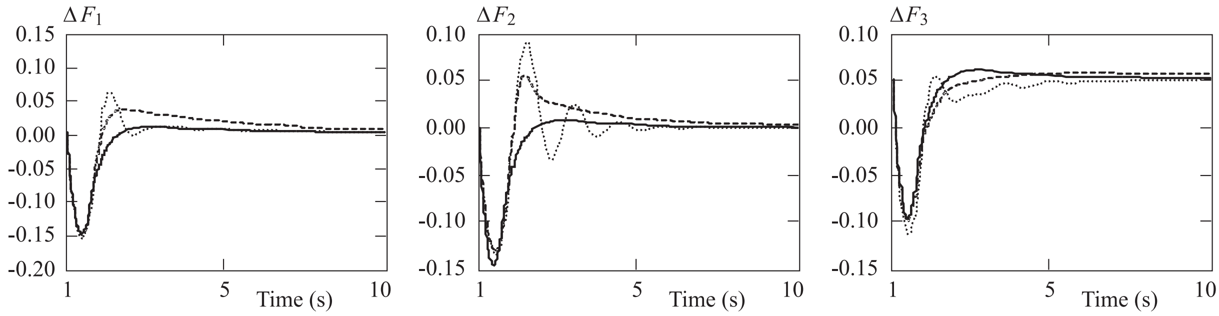

Fig. 11. Frequency deviation of three areas. Solid (MFPID), Dashed (Mixed H_2/H_∞), Dotted (FPID).

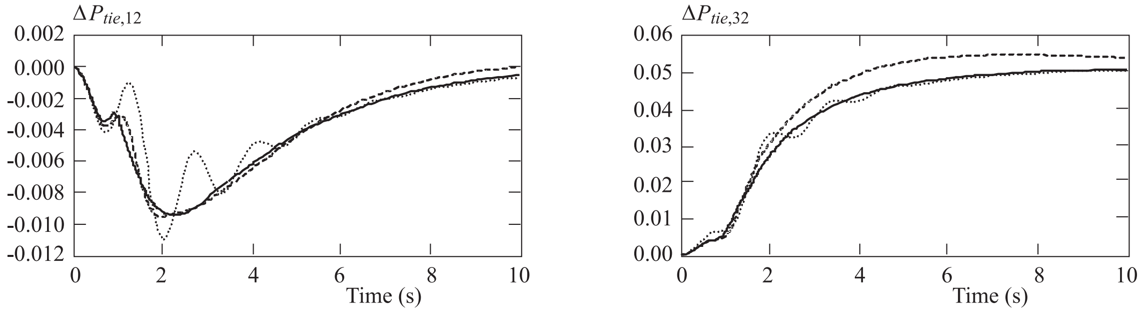

Fig. 12. Deviation of tie line power flow. Solid (MFPID), Dashed (Mixed H_2/H_∞), Dotted (FPID).

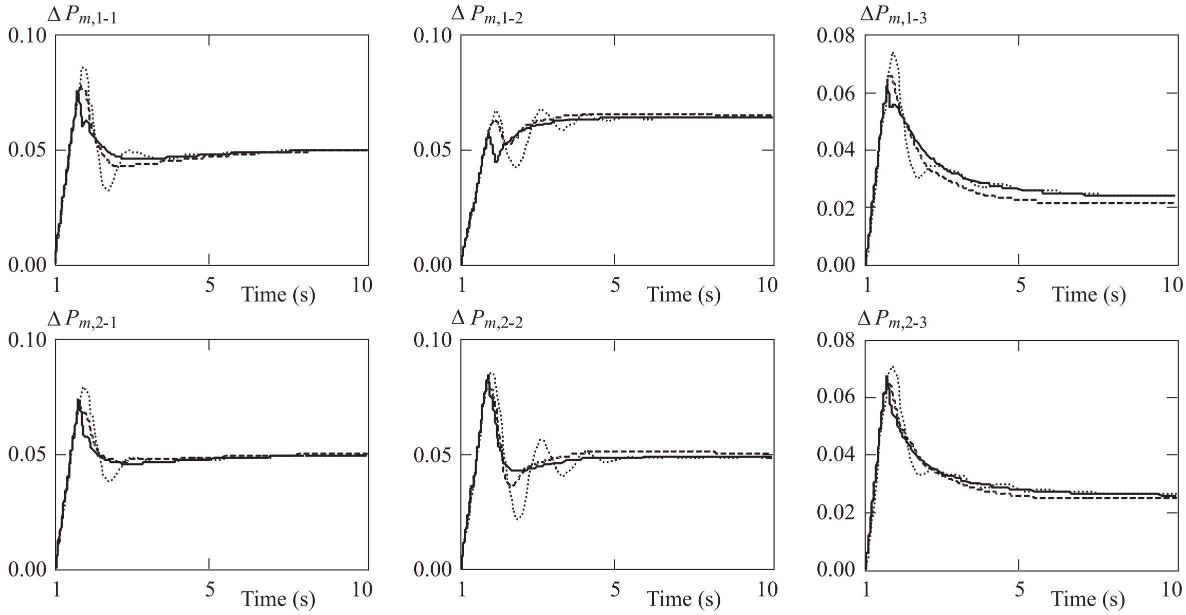

Fig. 13. GENCOs powerchange. Solid (MFPID), Dashed (Mixed H_2/H_∞), Dotted (FPID).

Matrix Inequality (LMI) technique. Here we only represent the result controllers which are dynamic type and are as follows:

$$
\begin{aligned}
K_{1mix}(s) &= \frac{-0.0161s^2+0.0099s-0.0097}{s^3+10.984s^2+21.5941s+12.1933}\,,\\
K_{2mix}(s) &= \frac{-0.0147s^2+0.0092s-0.0148}{s^3+10.17s^2+19673s+15.478}\,,\\
K_{3mix}(s) &= \frac{-0.01617s^2+0.00107s-0.0101}{s^3+12.181s^2+24.9846s+14.4173}\,.
\end{aligned}
\tag{13}
$$

4.1 Scenario 1: Poolco Based Transactions

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

$$
AGPM^\top = \begin{bmatrix} 0.5 & 0.5 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.5 & 0.5 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.5 & 0.5 \end{bmatrix}
$$

The frequency deviation of three areas, GENCOs power and tie-line power flow for the operation condition case B are depicted in Figs. 8–10. Using the proposed method, the frequency deviation of all areas and the tie-line power are quickly driven back to zero and has not any overshoots (Fig. 10). Since there are no contracts between areas, the scheduled steady state power flows over the tie-line are zero. Also the actual generated powers of GENCOs, according to (8), properly converge to the desired value in steady state. *ie*:

$$\Delta P_{M,1-1} = 0.05\,\text{pu.MW}, \quad \Delta P_{M,2-1} = 0.05\,\text{pu.MW},$$
$$\Delta P_{M,1-2} = 0.05\,\text{pu.MW}, \quad \Delta P_{M,2-2} = 0.05\,\text{pu.MW},$$
$$\Delta P_{M,1-3} = 0.05\,\text{pu.MW}, \quad \Delta P_{M,2-3} = 0.05\,\text{pu.MW},$$

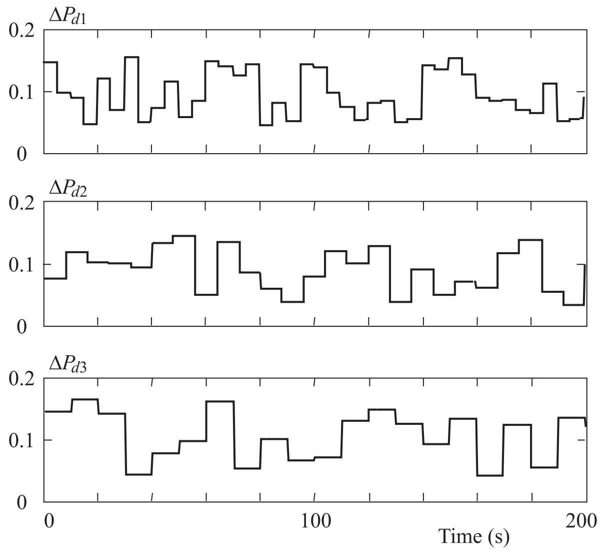

Fig. 14. The proposed multi stage fuzzy PID controller.

4.2 Scenario 2: Combination of Poolco and Bilateral Based Transactions

In this scenario, DISCOs have the freedom to have a contract with any GENCO in their or another areas. Consider that all the DISCOs contract with the available GENCOs for power as per following AGPM:

$$AGPM^{\top} = \begin{bmatrix} 0.25 & 0.5 & 0 & 0.25 & 0 & 0 \\ 0.25 & 0 & 0.25 & 0.25 & 0.25 & 0 \\ 0 & 0 & 0.75 & 0 & 0 & 0.25 \end{bmatrix}$$

Power system responses for operating point case C are shown in Figs. 11–13. Using the proposed method, the frequency deviation of the three areas are quickly driven back to zero and has very small settling time and overshoot. Also the tie-line power flow properly converges to the specified value, of (5), in the steady state (Fig. 12), *ie*; $\Delta P_{tie12,sch} = 0$ pu and $\Delta P_{tie32,sch} = -0.05$ pu. The actual generated powers of GENCOs properly reach the desired value (Fig. 13) in the steady state as given by (8).

$$\Delta P_{M,1-1} = 0.05\,\text{pu.MW}, \quad \Delta P_{M,2-1} = 0.05\,\text{pu.MW},$$
$$\Delta P_{M,1-2} = 0.1\,\text{pu.MW}, \quad \Delta P_{M,2-2} = 0.05\,\text{pu.MW},$$
$$\Delta P_{M,1-3} = 0.025\,\text{pu.MW}, \quad \Delta P_{M,2-3} = 0.025\,\text{pu.MW}.$$

4.3 Scenario 3: Contract Violation

Consider scenario 2 again in case A. Assume, in addition to the specified contracted load demands 0.1 pu, a bounded random step load change as a large uncontracted demand (shown in Fig. 14) appears in each control area, where

$$-0.07\,(\text{pu}) \leq \Delta P_{di} \leq 0.07\,(\text{pu}).$$

The purpose of this scenario is to test the robustness of the proposed controller against uncertainties and random large load disturbances. The deviation of frequency and tie line power flows fore operating condition case A are shown in Figs. 15, and 16 respectively.

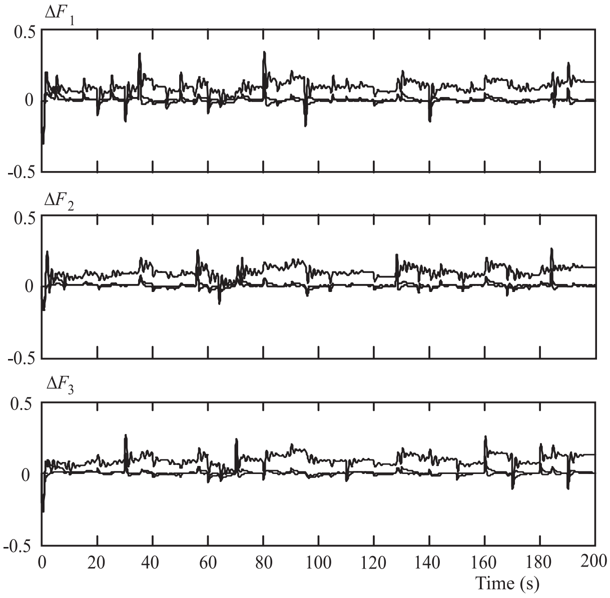

Fig. 15. Frequency deviation of three areas. Solid (MFPID), Dashed (FPID), Dotted (Mixed H_2/H_∞).

From Fig. 16, it can be seen that the MSFPID controller tracks the load fluctuations and meet robustness for a wide range of load disturbance and plant parameter changes.

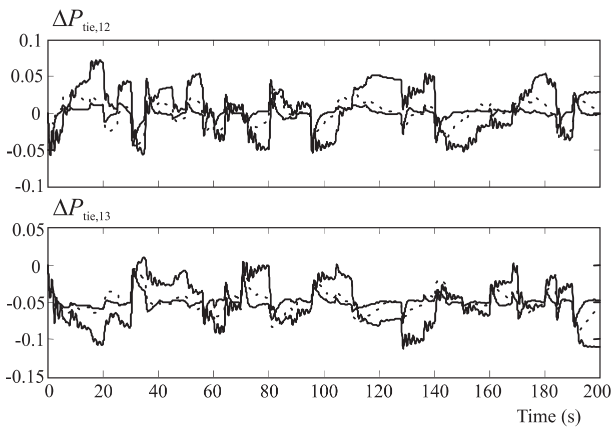

Fig. 16. Deviation of tie line power flow. Solid (MFPID), Dashed (FPID), Dotted (Mixed H_2/H_∞).

Table 6. Performance indices values

Scenario		ISE			ITAE			ITSE			FD		
		MFPID	FPID	H_2/H_∞	MFPID	FPID	H_2/H_∞	MFPID	FPID	H_2/H_∞	MFPID	FPID	H_2/H_∞
1	Case A	25.5	29.06	36.13	26.24	117.45	67.71	14.06	24.07	26.16	48.23	53.73	160.09
	Case B	25.19	26.43	29.08	25.08	109.48	36.05	13.82	20.41	18.01	48.16	49.03	177.35
	Case C	25.74	32.061	49.63	29.09	123.96	124.54	14.15	28.79	43.81	48.64	103.42	448.15
2	Case A	29.47	33.43	41.57	26.32	125.78	75.80	16.32	28.78	30.25	48.07	115.93	152.22
	Case B	29.1	30.23	33.28	26.63	115.80	41.61	16.10	24.43	20.99	48.13	91.73	104.08
	Case C	29.87	37.63	57.57	27.59	133.79	126.60	16.49	34.49	50.22	48.20	130.59	310.12

To demonstrate performance robustness of the proposed method, the ITAE, ITSE, ISE based on ACEi and Figure of Demerit (FD) based on the system performance characteristics are being used as:

$$ITEA = 100\int_0^{10} t\big(|ACE_1(t)| + |ACE_2(t)| + |ACE_3(t)|\big)\,\mathrm{d}t\,, \tag{13}$$

$$ITSE = 1000\int_0^{10} t\big(ACE_1^2(t) + ACE_2^2(t)ACE_3^2(t)\big)\mathrm{d}t, \tag{14}$$

$$ISE = 1000\int_0^{10} \big(ACE_1^2(t) + ACE_2^2(t)ACE_3^2(t)\big)\mathrm{d}t, \tag{15}$$

$$FD = (OS \times 100)^2 + (FU \times 40)^2 + (SU \times 500)^2 + (Ts \times 3)^2. \tag{16}$$

Where, Overshoot (OS), First Undershoot (FU), Second Undershoot (SU) and settling time (for 3 % band of the total load demand in area1) of frequency deviation area 1 is considered for evaluation of the FD. The numerical results for operating conditions case A, B and C under scenario 1 and 2 are listed in Table 6. Examination of Table 6 reveals that the performance of the proposed MSFPID controller is better than the FPID and mixed H_2/H_∞ controllers.

5 CONCLUSIONS

A new multi stage fuzzy PID type controller for the LFC problem in the restructured power systems is proposed using the modified LFC scheme in this paper. This control strategy was chosen because of increasing the complexity and changing structure of the restructured power systems. This newly developed control strategy combines advantage of the fuzzy PD and integral controllers for achieving the desired level of robust performance, such as precise reference frequency tracking and disturbance attenuation under a wide range of area-load changes and disturbances. The salient feature of proposed method is that it does not require an accurate model of the LFC problem and the design process is lower than the other fuzzy PID controllers. Moreover, it has simple structure and is easy to implement which ideally useful for the real world power system. The MSFPID controller was tested on a three-area restructured power system to demonstrate robust performance for the three possible contracted scenarios under different operating conditions. Simulation results show that the proposed strategy is very effective and guarantees good robust performance against parametric uncertainties, load changes and disturbances even in the presence of GRC. The system performance characteristics in terms of 'ITAE', 'ITSE', ISE' and 'FD' indices reveal that the proposed MSFPID has a promising control scheme for the LFC problem and superior than the CFPID and H_2/H_∞ controllers.

Appendix A: Nomenclature

F	area frequency
P_{Tie}	net tie-line power flow
P_T	turbine power
P_V	governor valve position
P_C	governor set point
ACE	area control error
α	ACE participation factor
Δ	deviation from nominal value
K_P	subsystem equivalent gain
T_P	subsystem equivalent time constant
T_T	turbine time constant
T_G	governor time constant
R	droop characteristic
B	frequency bias
T_{ij}	tie line synchronizing coefficient between areas i and j
P_d	area load disturbance
P_{Lj-i}	contracted demand of Disco j in area i
P_{ULj-i}	un-contracted demand of Disco j in area i
$P_{m,j-i}$	power generation of GENCO j in area i
P_{Loc}	total local demand
η	area interface
ζ	scheduled power tie line power flow deviation ($\Delta P_{tie,sch}$.)

Appendix B: System Parameters

Table 7. GENCOs parameter

MVA_{base} (1000 MW) Parameter	GENCOs (k in area i)					
	1–1	2–1	1–2	2–2	1–3	2–3
Rate (MW)	1000	800	1100	900	1000	1020
T_T (sec)	0.36	0.42	0.44	0.4	0.36	0.4
T_G (sec)	0.06	0.07	0.06	0.08	0.07	0.08
R (Hz/pu)	2.4	3.3	2.5	2.4	2.4	3.3
α	0.5	0.5	0.5	0.5	0.5	0.5

Table 8. Control area parameters

Parameter	Area-1	Area-2	Area-3
M	0.1667	0.2	0.1167
D	0.0084	0.014	0.011
B (pu/Hz)	0.8675	0.785	0.870
T_{ij} (pu/Hz)	$T_{12} = T_{13} = 0.545$		

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