Fuzzy C-means load frequency controller in deregulated power environment

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Abstract: The load frequency control (LFC) problem has been a major subject in the power system design/operation. The evolution of many socialised companies for power generation affects the formulation of LFC problem. In the present paper, a fuzzy load frequency controller with minimum rule-base is proposed. The optimal rule base for the proposed controller is obtained from fuzzy C-means clustering technique. The efficacy of the proposed fuzzy C-means load frequency controller is verified and compared with existing techniques in the literature for a three area interconnected power system in deregulated environment for various operating conditions under different nonlinearities. The proposed controller is tested for practical generation plants (NTTPS, KTPS, and RTPS) in India.

Keywords: load frequency control; LFC; PID controller; fuzzy PID controller; fuzzy C-means controller; deregulated power system.

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1 Introduction

In nineties, many power networking companies and electrical utilities around the world have been forced to adopt a modified way of operation from vertically integrated mechanism to open market systems. It has been analysed that power networking companies have become one of the most profitable ancillary services. In power system, mismatches between the generation and demand lead to power imbalance which causes deviations in frequency and tie line power from their scheduled values (Liu et al., 2003). These mismatches are controlled by regulating the power output of generators within a prescribed area. The main purpose of the load frequency control (LFC) is to maintain the frequency of individual area and tie-line power flow in an interconnected power system within the specified tolerance, by adjusting the MW outputs of the generators for load fluctuations (Yang et al., 1998). With the restructuring of electric markets, the requirement for LFC is made to be expanded such that it includes the planning functions that insure the resources needed for its implementation are within the functional requirements (Donde et al., 2001). While the basic approach to LFC is kept the same, the reconstructed power system after deregulation, operation, simulation and optimisation has to be restructured. In this case, a distribution company (DISCOM) may undergo/take-up a contract individually with GENCOs or independent power producers (IPPs) for distributing power in different areas under the supervision of independent system operator (Singh Parmar et al., 2014). The necessity of deregulation of the power system is motivated with an increasing number of IPPs where the power can be sold at a competitive price and best performs all functions involved in generation, transmission, distribution according to the retail sales. Hence, a concept of DISCOM participation matrix (DPM) is used to understand how the contracts between DISCOMs and GENCOS are being implemented (Daneshfar, 2013). The information flow of the contracts is superimposed on the traditional AGC system (Sudha et al., 2012). Literature (Sakis Meliopoulos et al., 1999) shows that some of the research studies on LFC are/have been taking place in a deregulated environment. The methods of controlling must maintain the best ability to track the contracted or non-contracted demands and must be usable in a practical environment (Ying, 2006). To improve the dynamic response of system under competitive conditions, the conventional control strategy for the LFC problem has been solved with an integral controller which exhibits poor dynamic performance with zero steady state error (Sudha and Vijaya Santhi, 2012). Literature (Hiyama and Sameshima, 1991) presents many controllers for LFC problems which obtain a better dynamic performance, where the most employed one is the conventional fixed gain controller like a proportional integral (PI) controller or a PID controller (Bezdek, 1981). Fixed gain controllers rely on linear design methods and may not provide appropriate regulating signals over a wide range of operating conditions and disturbances (Sudha and Vijaya Santhi, 2011). Hence, to cover a wide range based on nonlinear conditions, a linguistic approach to develop fuzzy logic controller (FLC) is employed (El-Metwally, 2001; Srikanth and Vinod Kumar, 2004).

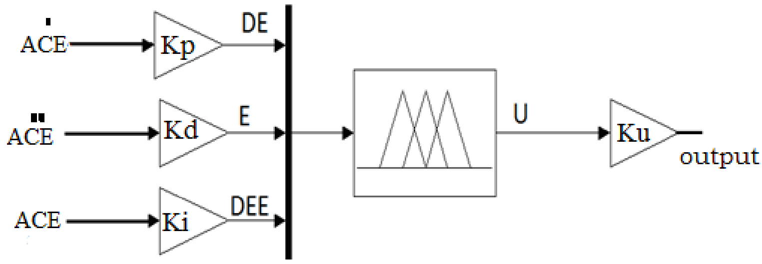
FLCs have been successfully applied in various fields of engineering and they allow nonlinear input/output relationships to be expressed as a set of linguistic fuzzy rules. Most fuzzy systems have expertise of human that can capture desired input/output relationships for a particular process (Shayeghi et al., 2007; Bhatt et al., 2010). It is difficult to examine the behaviour of captured data from complex system to find the number of contributed rules for FPID controller (Rakhshani and Sadeh, 2010; Shayanfar et al., 2006). So, to handle this difficulty, researchers had put forth much effort to develop alternative design methods (Rashedi et al., 2010). Recently, methods to extract fuzzy rule base have incorporated clustering techniques that require the users to pre-specify the structure of the rule base which includes number of rules per class or number of membership functions per input feature, along with initial values for the adjustable parameters (Rakhshani and Sadeh, 2010). Clustering is the unsupervised classification of Patterns such as observations, data items, or feature vectors into clusters i.e., groups. Fuzzy clustering is also useful for constructing fuzzy if-then rules from input output data. The structure of the rules depends on the system considered for study. Clustering algorithms typically require the pre-specified number of cluster centres and their locations those clusters are then adapted in such a way to represent a set of model data points to cover the range of data behaviour. The fuzzy C-means (FCM) algorithm method is a well-known example of such clustering algorithms (Sudha et al., 2012).

This paper analyses an automatic rule generation and structure optimization by deriving the number of clusters required to extract contributed rule base of a fuzzy load frequency controller (FLFC) (Sadeh and Rakhshani, 2008). These clusters are validated on data obtained in the deregulated environment of three area interconnected power system for wide range of load variations under different nonlinearities. The performance of the proposed controller is tested on practical generation plants in Andhra Pradesh (India). Having Dr. Narla Tata Rao thermal power station (NTTPS) with two units (500 mw, 210 mw) in area 1, Kothagudem thermal power station (KTPS) with two units (500 mw, 250 mw) in area 2, Rayalaseema thermal power station (RTPS)with two units (210 mw, 210 mw) in area 3 consider as three area power system.

2 Design of a fuzzy logic PID controller

The structure of FLC is similar to PID controller as shown in Figure 1.

Figure 1 Structure of FLC



2.1 FLC fuzzification module

The normalised inputs of the fuzzification module are $x(\dot{ACE}), x(ACE)$ and $x(\ddot{ACE})$ which are equal to $G_p \dot{ACE}, G_i ACE$ and $G_d \ddot{ACE}$ respectively. G_p, G_i and G_d are normalisation or scaling factor of the inputs the fuzzy sets positive (P), zero (Z), negative (N). The MF of these are defined by $\mu_p(.)$, $\mu_N(.)$ and $\mu_Z(.)$ or $\mu_1(.)$, $\mu_{-1}(.)$ and $\mu_0(.)$.

Let the number of fuzzy sets of the inputs be the same and the MF be identical. If the members of the input fuzzy set N, Z and P are $X_{-1}(.)$, $X_0(.)$, $X_1(.)$ respectively, then the output function is derived using the following control rules, where i, j and k can take any value from –1, 0, +1.

IF $x(\dot{ACE})$ is x_i and $x(ACE)$ is x_j and $x(\ddot{ACE})$ is x_k THEN output is $U_{-(i+j+k)}$.

This fuzzy rule is called a linear control rule because the linear function is employed to relate the indices of the input fuzzy sets to the index of the output fuzzy set (Vakula and Sudha, 2011).

2.2 FLC rule module

Since the control rules are linear, the number of members of the output fuzzy set members will be equal to $(3N - 2)$ for $N \geq 3$, where N is the number of MF of each input. In the present case, $N = 3$, hence the output has seven members in the output fuzzy set. The seven members of the output fuzzy set are negative big (NB), negative medium (NM), negative small (NS), zero (Z), positive small (PS), positive medium (PM), positive big (PB) and are represented by U_{-3}, U_{-2}, U_{-1}, U_0, U_1, U_2, U_3. The member of the output MF should be symmetrical in its central value and the shape of all the members of MF should be the same (Vakula and Sudha, 2011). In this case a triangular shape is considered as in case of the three MF of each input is 3 × 3 × 3 i.e., 27 rules are in Table 1.

Table 1 Representation of rules in linguistic form

Rule	*DE*	*E*	*DEE*	*Output*	*Rule*	*DE*	*E*	*DEE*	*Output*
1	P	P	P	NB	15	N	Z	N	PM
2	P	P	Z	NM	16	N	N	P	PS
3	P	P	N	NS	17	N	N	Z	PM
4	P	Z	P	NM	18	N	N	N	PB
5	P	Z	Z	NS	19	Z	P	P	NM
6	P	Z	N	Z	20	Z	P	Z	NS
7	P	N	P	NM	21	Z	P	N	Z
8	P	N	Z	Z	22	Z	Z	P	NS
9	P	N	N	PS	23	Z	Z	Z	Z
10	N	P	P	NS	24	Z	Z	N	PS
11	N	P	Z	Z	25	Z	N	P	Z
12	N	P	N	PS	26	Z	N	Z	PS
13	N	Z	P	Z	27	Z	N	N	PM
14	N	Z	Z	PS					

2.3 *FLC defuzzification module*

The centroid method is used for defuzzification considering the i^{th}, j^{th} and k^{th} MF of $\dot{\text{ACE}}$, ACE, $\ddot{\text{ACE}}$ respectively

$$U = \frac{\sum \begin{Bmatrix} \textit{Membership value of input} \\ \times \textit{output corresponding to the membership value of input} \end{Bmatrix}}{\sum \{\textit{membership value of input}\}}$$
$$U = \frac{\sum v(i, j, k)}{\sum \mu(i, j, k)} \tag{1}$$

where $v(i, j, k)$ is the incremental control output contributed by any fuzzy control rule in Table 1.

Fuzzy logic 'and' is used to execute the IF side of the fuzzy control rule that is

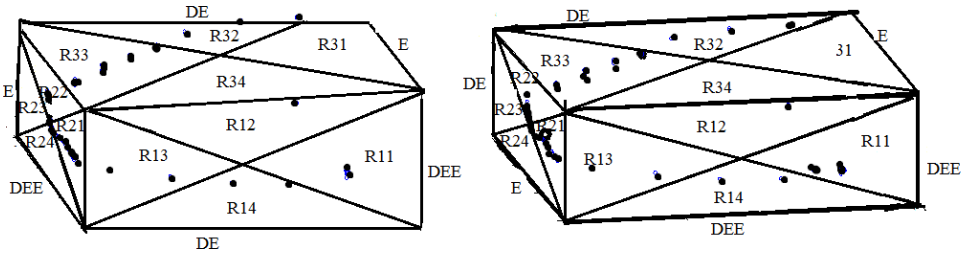
$$\mu(i, j, k) = Min\left(\mu_i(\dot{\text{ACE}}), \mu_j(\text{ACE}), \mu_k(\ddot{\text{ACE}})\right) \tag{2}$$

Since the membership function of the 'output' is symmetrical about its central value the 'THEN' side of the control rule is

$$\begin{aligned} v(i, j, k) &= \mu(i, j, k).\gamma_{-(i+j+k)} \\ &= -Min\left(\mu_i(\dot{\text{ACE}}), \mu_j(\text{ACE}), \mu_k(\ddot{\text{ACE}})\right)(i+j+k)V \end{aligned} \tag{3}$$

To calculate the IF side of the control rule the MF diagram of the three inputs $x(\mathrm{A\dot{C}E})$, $x(\mathrm{ACE})$, $x(\mathrm{A\ddot{C}E})$ are divided into intervals as represented in Figure 2(a). The purpose of dividing the input space is to find unique relationship among the three inputs. Using centroid defuzzifier the output equations in the 24 regions are shown in Table 2.

Figure 2 Division of input spaces and spaces with clusters (see online version for colours)



(a) (b)

The three-dimensional graph in Figure 2 is divided into three two-dimensional graphs to evaluate the resultant output. Every two-dimensional graph is subdivided into eight regions and the evaluation procedure for a control rule using the two-dimensional graph is as follows:

Step 1: $Min((\mu_j(E), \mu_k(DE\ E))$ in any region of Figure 2 $\mu(i, j, k) = Min(\mu_j(E),$ *of step 1*, $\mu_i(DE))$ in region R_{33}. The evaluation procedure is illustrated for the region R_{14}.

For example: Rule: 23 $\mu(Z, N, N) = Min[\mu_Z(DE), \mu_Z(E), \mu_Z(DEE)] = \mu_Z(E)$.

To evaluate the minimum of the above rule, the Step 1 is executed first, from Figure 2, it is evident that $\mu_N(E)$ is minimum in the regions R_{11}, R_{14}, R_{21}, R_{22}, R_{32}, R_{33}.

Therefore, in region R_{14}: $Min((\mu_N(E), \mu_N(DEE)) = \mu_N(DE))$.

Hence, $\mu(i, j, k) = Min(\mu_N(E)$ *of step 1*, $\mu_Z(DE))$ of in region R_{24} and $\mu(i, j, k) = \mu_N(E)$. Similarly for rules 19, 20, 21 22, 24, 25, 26, and 27 the resultant output is derived using Figure 2(a). Therefore, the centroid defuzzifier in region R_{14} is given by

$$\begin{aligned}\sum \mu(i, j, k) = {} & \mu_P(DEE) + \mu_Z(DE) + \mu_Z(DEE) + \mu_Z(DE) + \mu_N(E) \\ & + \mu_P(E) + \mu_Z(DE) + \mu_Z(E) + \mu_Z(DEE)\end{aligned} \tag{4}$$

Substituting the values of membership function using equation (4) in regions, R_{11}, R_{14}, R_{21}, R_{22}, R_{32}, R_{33} the output equations obtained using Table 2. Therefore, in the above six regions, the contributed rules for the output under the worst operating conditions are identified as rules – 19, 20, 21, 22, 23, 24, 25, 26, 27. Using centroid defuzzifier the output equations in the 24 regions shown in Table 2. Thus, a three-input three membership function FLC is a compact FLC with nine Rules, proposed in this section.

The output consists of two parts, of which the first part is a three dimensional multilevel relay with respect to i, j, k. The multi level relay can be denoted as

$$Relay(i, j, k) = -(i + j + k + 1.5)\frac{1}{2} = -\left[(i + 0.5) + (j + 0.5) + (k + 0.5)\right]\frac{1}{2} \tag{5}$$

Table 2 Fuzzy logic output equations in the 24 regions

Regions	*U*
(R11 or R21) and (R13 or R23)	$-(i+j+k+1.5)\frac{1}{2}-\left(\left[\mathrm{G}_p\,\mathrm{A\dot{C}E}-(i+0.5)\right]/2-2\left\|\mathrm{G}_p\,\mathrm{A\dot{C}E}-(i+0.5)\right\|-\left\|\mathrm{G}_i\,\mathrm{ACE}-(j+0.5)\right\|\right)\times\frac{1}{2}$
(R11 or R21) and R13 or R23)	$-(i+j+k+1.5)\frac{1}{2}-\left(\left[\mathrm{G}_p\,\mathrm{A\dot{C}E}-(i+0.5)\right]/2a-2\left\|\mathrm{G}_p\,\mathrm{A\dot{C}E}-(i+0.5)\right\|-\left\|\mathrm{G}_d\,\mathrm{A\ddot{C}E}-(k+0.5)\right\|\right)\times\frac{1}{2}$
(R31 or R21) and (R33 or R23)	$-(i+j+k+1.5)\frac{1}{2}-\left(\left[\mathrm{G}_d\,\mathrm{A\ddot{C}E}-(k+0.5)\right]/2-2\left\|\mathrm{G}_p\,\mathrm{A\dot{C}E}-(i+0.5)\right\|-2\left\|\mathrm{G}_d\,\mathrm{A\ddot{C}E}-(k+0.5)\right\|\right)\times\frac{1}{2}$
R31 or R21) and (R33 or R23)	$-(i+j+k+1.5)\frac{1}{2}-\left(\frac{\left[\left[\mathrm{G}_p\,\mathrm{A\dot{C}E}-(i+0.5)\right]+\left[\mathrm{G}_i\,\mathrm{ACE}-(j+0.5)a\right]+\left[\mathrm{G}_d\,\mathrm{A\ddot{C}E}-(k+0.5)\right]\right]}{2-2\left\|\mathrm{G}_p\,\mathrm{A\dot{C}E}-(i+0.5)\right\|-\left\|\mathrm{G}_i\,\mathrm{ACE}-(j+0.5)\right\|}\right)\times\frac{1}{2}$
(R31 or R11) and (R33 or R13)	$-(i+j+k+1.5)\frac{1}{2}-\left(\frac{\left[\left[\mathrm{G}_p\,\mathrm{A\dot{C}E}-(i+0.5)\right]+\left[\mathrm{G}_i\,\mathrm{ACE}-(j+0.5)\right]+\left[\mathrm{G}_d\,\mathrm{A\ddot{C}E}-(k+0.5)\right]\right]}{2-2\left\|\mathrm{G}_p\,\mathrm{A\dot{C}E}-(i+0.5)\right\|-\left\|\mathrm{G}_d\,\mathrm{A\ddot{C}E}-(k+0.5)\right\|}\right)\times\frac{1}{2}$
R31 or R11) and (R33 or R13)	$-(i+j+k+1.5)\frac{1}{2}-\left(\frac{\left[\left[\mathrm{G}_p\,\mathrm{A\dot{C}E}-(i+0.5)\right]+\left[\mathrm{G}_i\,\mathrm{ACE}-(j+0.5)\right]+\left[\mathrm{G}_d\,\mathrm{A\ddot{C}E}-(k+0.5)\right]\right]}{2-\left\|\mathrm{G}_p\,\mathrm{A\dot{C}E}-(i+0.5)\right\|-2\left\|\mathrm{G}_d\,\mathrm{A\ddot{C}E}-(k+0.5)\right\|}\right)\times\frac{1}{2}$
(R12 or R22) and (R14 or R24)	$-(i+j+k+1.5)\frac{1}{2}-\left(\left[\mathrm{G}_i\,\mathrm{A\dot{C}E}-(j+0.5)\right]/2-\left\|\mathrm{G}_p\,\mathrm{A\dot{C}E}-(i+0.5)\right\|-2\left\|\mathrm{G}_i\,\mathrm{ACE}-(j+0.5)\right\|\right)\times\frac{1}{2}$
(R12 or R22) and (R14 or R24)	$-(i+j+k+1.5)\frac{1}{2}-\left(\left[\mathrm{G}_i\,\mathrm{A\dot{C}E}-(j+0.5)\right]/2-\left\|\mathrm{G}_d\,\mathrm{A\ddot{C}E}-(k+0.5)\right\|-2\left\|\mathrm{G}_i\,\mathrm{ACE}-(j+0.5)\right\|\right)\times\frac{1}{2}$
(R32 or R22) and (R34 or R24)	$-(i+j+k+1.5)\frac{1}{2}-\left(\left[\mathrm{G}_d\,\mathrm{A\ddot{C}E}-(k+0.5)\right]/2-\left\|\mathrm{G}_d\,\mathrm{A\ddot{C}E}-(k+0.5)\right\|-2\left\|\mathrm{G}_i\,\mathrm{ACE}-(j+0.5)\right\|\right)\times\frac{1}{2}$
(R32 or R22) and (R34 or R24)	$-(i+j+k+1.5)\frac{1}{2}-\left(\frac{\left[\left[\mathrm{G}_p\,\mathrm{A\dot{C}E}-(i+0.5)\right]+\left[\mathrm{G}_i\,\mathrm{ACE}-(j+0.5)\right]+\left[\mathrm{G}_d\,\mathrm{A\ddot{C}E}-(k+0.5)\right]\right]}{2-\left\|\mathrm{G}_p\,\mathrm{A\dot{C}E}-(i+0.5)\right\|-2\left\|\mathrm{G}_i\,\mathrm{ACE}-(j+0.5)\right\|}\right)\times\frac{1}{2}$
(R32 or R12) and (R34 or R14)	$-(i+j+k+1.5)\frac{1}{2}-\left(\frac{\left[\left[\mathrm{G}_p\,\dot{\delta}-(i+0.5)\right]+\left[\mathrm{G}_i\,\mathrm{ACE}-(j+0.5)\right]+\left[\mathrm{G}_d\,\mathrm{A\ddot{C}E}-(k+0.5)\right]\right]}{2-\left\|\mathrm{G}_d\,\mathrm{A\ddot{C}E}-(k+0.5)\right\|-\left\|\mathrm{G}_i\,\mathrm{ACE}-(j+0.5)\right\|}\right)\times\frac{1}{2}$
(R32 or R12) and (R34 or R14)	$-(i+j+k+1.5)\frac{1}{2}-\left(\frac{\left[\left[\mathrm{G}_p\,\mathrm{A\dot{C}E}-(i+0.5)\right]+\left[\mathrm{G}_i\,\mathrm{ACE}-(j+0.5)\right]+\left[\mathrm{G}_d\,\mathrm{A\ddot{C}E}-(k+0.5)\right]\right]}{2+\left\|\mathrm{G}_d\,\mathrm{A\ddot{C}E}-(k+0.5)\right\|-2\left\|\mathrm{G}_i\,\mathrm{ACE}-(j+0.5)\right\|}\right)\times\frac{1}{2}$

The multilevel relay contributes its control action according to the absolute position with respect to the entire scaled input state plane, of the centre of the square in which the current scale input G_i ACE, G_p $\dot{\text{ACE}}$, G_d $\ddot{\text{ACE}}$ lies. Therefore the multilevel relay can be called as the 'global' multi level relay. The second part is a nonlinear controller. The gains of the nonlinear controller are calculated according to the relative position of the current scaled input G_i ACE, G_p $\dot{\text{ACE}}$, G_d $\ddot{\text{ACE}}$ with respect to the centre of the square which consists of the current scaled input. The role of this nonlinear controller is to locally adjust the control action generated by the global multilevel relay and hence it is called the local nonlinear controller.

The nonlinear controller is a nonlinear PID controller U_{nl} with changing steady state $((i + 0.5) / G_p, (j + 0.5) / G_i, (k + 0.5) / G_d,$

$$U_{nl} = -\left(k'_p \left[\dot{\text{ACE}} - \frac{(i+0.5)}{G_p} \right] + k'_i \left[\text{ACE} - \frac{(j+0.5)}{G_i} \right] + k'_d \left[\ddot{\text{ACE}} - \frac{(k+0.5)}{G_d} \right] \right) \tag{6}$$

where

$$k'_p = \frac{G_p}{2}\beta, k'_i = \frac{G_i}{2}\beta, k'_d = \frac{G_d}{2}\beta \tag{7}$$

where β is a nonlinear term and has different expressions in different regions. For example in the region of IC5' and (R33 or R23) and IC2' and (R31 or R23)

$$\beta = \frac{1}{1 - \left|G_p \dot{\text{ACE}} - (i+0.5)\right| - \left|G_i \text{ACE} - (j+0.5)\right| 0.5} \tag{8}$$

At equilibrium point, $|G_p \dot{\text{ACE}} - (i+0.5)| \to 0$, $|G_i \text{ACE} - (j+0.5)| \to 0$, $|G_d \ddot{\text{ACE}} - (k+0.5)| \to 0$, and $\beta = 1$ therefore at equilibrium point

$$k'_p = \frac{G_p}{2}, k'_i = \frac{G_i}{2}, k'_d = \frac{G_d}{2} \tag{9}$$

$$U_{pid} = (i + j + k + 1.5)G_u + \left[\overline{k_p} \dot{\text{ACE}} + \overline{k_i} \text{ACE} + \overline{k_d} \ddot{\text{ACE}} \right] \tag{10}$$

where $\overline{k_p} = k'_p G_u, \overline{k_i} = k'_i G_u, \overline{k_d} = k'_d G_u$.

Therefore, at the equilibrium point, $|G_p \dot{\text{ACE}} - (i+0.5)| \to 0$, $|G_i \text{ACE} - (j+0.5)| \to 0$, $|G_d \ddot{\text{ACE}} - (k+0.5)| \to 0$, and $\beta = 1$. Therefore, at the equilibrium,

$$\overline{k_p} = \frac{G_p G_u}{2}, \overline{k_i} = \frac{G_i G_u}{2}, \overline{k_d} = \frac{G_d G_u}{2} \tag{11}$$

Hence, it acts as a linear PID controller.

2.4 Tuning of FLC

The FLC is a nonlinear controller, which can act effectively both in linear as well as nonlinear models. From the above equations, the overall tuning of the FLC can be achieved to obtain the desired or optimal response by tuning the FLPSS parameters as linear equivalent to conventional PID controller (Vakula and Sudha, 2011). The parameters of the conventional PID stabiliser are used as the starting point to further tune the FLC. For the FLC considered, the G_p is calculated depending on the maximum value of the proportional input $\dot{\text{ACE}}$ without the controller so that the range of values of $\dot{\text{ACE}}$ fit into the UOD [–1 1] $G_p = \frac{1}{|\dot{\text{ACE}}_{\max}|}$. Using the value of G_p the remaining parameters can be found. The output is defined between a UOD [–1 1] therefore H = 1.

3 Cluster validation of FLC using FCM

For many cases of engineering applications, the number of cluster '*c*' can be known from the data. However, in some cases it would be reasonable to expect the substructure of clusters at more than one value of c. Hence, it is necessary to identify the value of '*c*' that gives the most reasonable number of clusters from the data considered for the analysis. This problem is defined as cluster validity (see Bezdek, 1981). If the data to be analysed is labelled, an absolute value of '*c*' does exist for cluster validity but does not exist for unlabeled data.

3.1 FCM algorithm

FCM is a method of clustering that allows one set of data belong to two or more clusters (Sudha et al., 2012). This method was first developed by Dunn in 1973 and improved by Bezdek in 1981 (Sadeh and Rakhshani, 2008). It is an iterative method which is based on minimisation of the following objective function, *J*

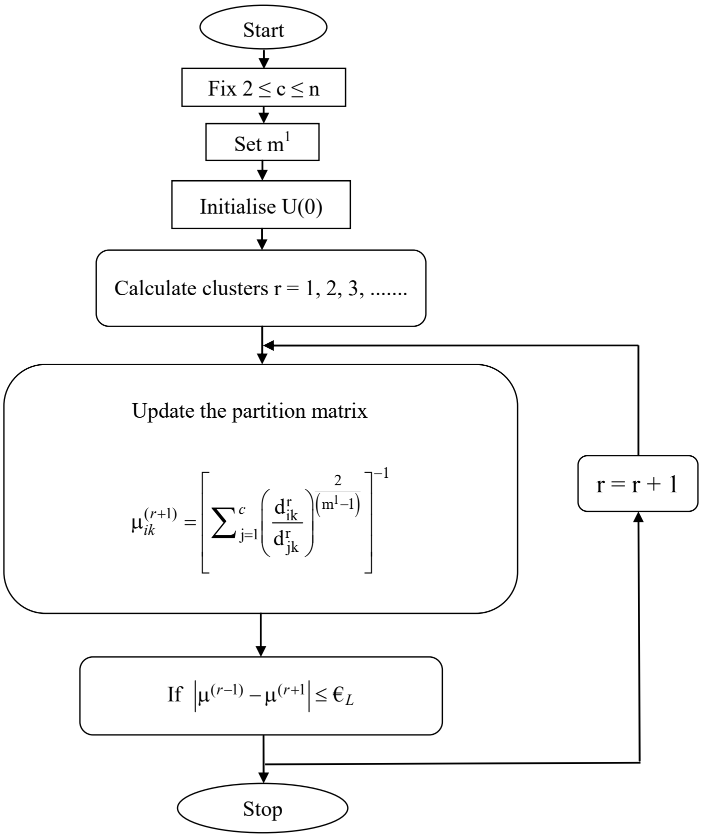
$$J_m = \sum_{i=1}^{n}\sum_{j=1}^{c} u_{ij}^m \left\|x_i - c_j\right\|^2, \qquad 1 \le m < \infty$$
$$\sum_{i=1}^{n}\left\|x_i - c_j\right\| = d_{ij} \tag{12}$$

where m is a real number > 1, u_{ij} is the degree of membership of x_i in the cluster k, x_i is the i^{th} of m-dimensional measured data, c_k is the m-dimension centre of the cluster, and ||*|| is any norm expressing the similarity between any measured data and the centre.

Through an iterative optimisation of *J*, fuzzy portioning is carried out by updating membership u_{ik} and the clusters c_k. This iteration ends if $\max_{ij}\{|u_{ij}^{(k+1)} - u_{ij}^{(k)}|\} < \varepsilon,$ where ε is a termination factor less than 1 and k is the numbers of iterations.

$$u_{ik} = \frac{1}{\sum_{q=1}^{c}\left(\frac{\left\|x_i - c_j\right\|}{\left\|x_i - c_q\right\|}\right)^{\frac{2}{m-1}}}, \quad c_j = \frac{\sum_{i=1}^{n} u_{ij}^m x_i}{\sum_{i=1}^{n} u_{ij}^m} \tag{13}$$

Figure 3 FCM optimisation process



3.2 Cluster validity with FCM

The function in the equation (13) is a *least squares* function, where the parameter n is the number of datasets and c is the number of partitions or classes into which one is trying to classify the datasets. The squared distance d_{ij}^2, is then weighted by a measure, $(u_{ij})^{m'}$ of the membership of x_k in the i^{th} cluster. The value of J is then a measure of the sum of all the *weighted* squared errors; this value is then minimised with respect to two constraint functions. The first, J_m is minimised with respect to the squared errors within each cluster, i.e., for each specific value of c. Simultaneously, the distance between cluster centres is maximised, i.e., max $\| \mathbf{v_i} - \mathbf{v_j} \|$ I not equal to j.

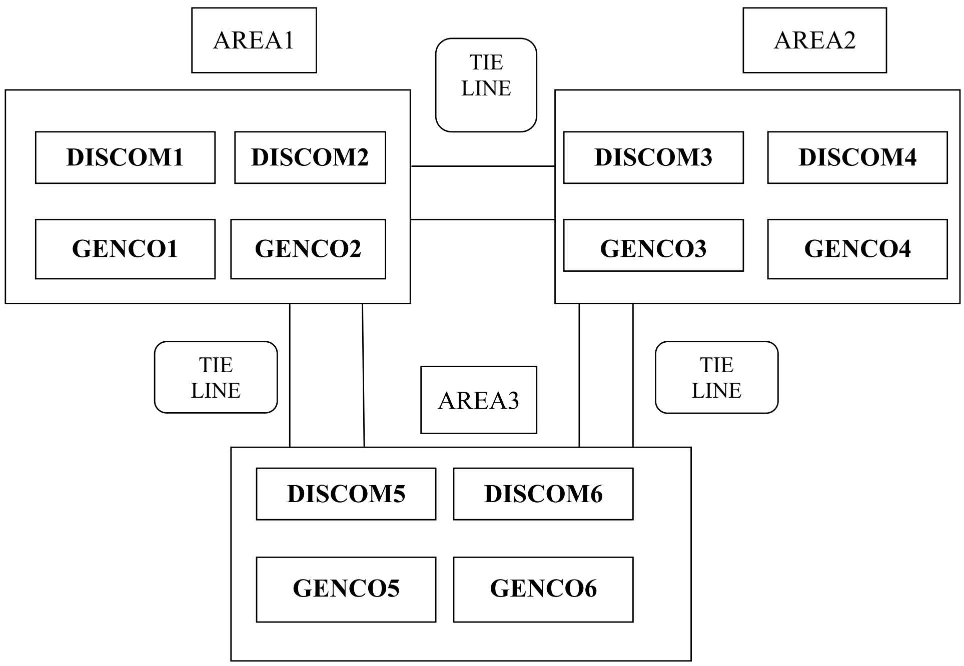
As indicated, the range for the membership exponent is $m' \in [1, \infty)$. For $m' = 1$, the distance norm is Euclidean and the clustering values becomes hard i.e., 0 or 1 and as $m' \to \infty$, the value of $J_m \to 1$. The exponent m' controls the extent of membership sharing between fuzzy clusters. Hence, optimum value of m' has to be 1.25 and convergence of the algorithm will become slower as the value of m' increases.

4 Case study

4.1 Modelling of three-area interconnected deregulated power systems

The concept of virtual integral utilities (VIU) will no longer exist in the competitive environment of power system. The deregulated power system consists of GENCOs, DISCOMs, TRANCOs and independent system operator. However the common aim of LFC is to restore the frequency and tie line power interchanges to their desired values for individual control area. The system considered for study is assumed to have three areas and each includes two GENCOS and two DISCOMS and the block diagram of generalised LFC scheme of a deregulated power system is shown in Figure 4. In the open market purchases, any GENCO in one area may supply its DISCOMs and DISCOMs in other two areas through tie-lines allowing power transfer between all three power system areas. In a deregulated power system having several GENCOS and DISCOMs, any DISCOM (Singh Parmar et al., 2014) may contract with any GENCO in another control area independently, is known as mutual transaction. These transactions are to be carried out through an independent system operator (ISO) (Shayeghi et al., 2005; Yang et al., 1998; Shayanfar et al., 2006).

Figure 4 Three area deregulated load frequency control



To visualise the contracts or transactions carried through ISO, the concept of 'DPM' will be used. DPM gives the participation of a DISCOM in contract with a GENCO. Any entry in DPM matrix will be a fraction of total load power contracted by a DISCOM toward a GENCO. Therefore, total of entries of a column belong to i^{th} DISCOM of DPM is

$$\sum_i cpf_{ij} = 1. \tag{15}$$

The corresponding DPM to the power system considered for study having three areas and each of them includes two DISCOM's and GENCOs is given in equation (14)

$$DPM = \begin{bmatrix} cpf_{11} & cpf_{12} & | & cpf_{13} & cpf_{14} & | & cpf_{15} & cpf_{16} \\ cpf_{21} & cpf_{22} & | & cpf_{23} & cpf_{24} & | & cpf_{25} & cpf_{26} \\ - & - & | & - & - & | & - & - \\ cpf_{31} & cpf_{32} & | & cpf_{33} & cpf_{34} & | & cpf_{35} & cpf_{36} \\ cpf_{41} & cpf_{42} & | & cpf_{43} & cpf_{44} & | & cpf_{45} & cpf_{46} \\ - & - & | & - & - & | & - & - \\ cpf_{51} & cpf_{52} & | & cpf_{53} & cpf_{54} & | & cpf_{55} & cpf_{56} \\ cpf_{61} & cpf_{62} & | & cpf_{63} & cpf_{64} & | & cpf_{65} & cpf_{66} \end{bmatrix} \tag{14}$$

where

$$cpf_{ij} = \frac{j^{th}\ DISCOM\ power\ demand\ out\ of\ i^{th}\ GENCO\ in\ p.u\ MW}{j^{th}\ DISCOM\ total\ power\ demand\ in\ p.u\ MW} \tag{15}$$

Whenever a load demanded by a DISCOM1 changes, it is observed as a local load change in the area 1, which is similar with other areas corresponds to the local loads ΔP_{D1}, ΔP_{D2}, ΔP_{D3}. This should be reflected in the block diagram of three area power system in deregulated environment at the point of input to the power system block. As there are two GENCOs in each area, area control error (ACE) signal has to be distributed among them in proportion to their participation in the AGC. The factor that distributes ACE to two GENCOs is termed as ACE participation factors (apf) (16)

Therefore

$$\sum_{k=1}^{n} apfk = 1 \tag{16}$$

where n is the number of GENCOs.

Thus, as a particular set of GENCOs is supposed to follow the load demanded by a DISCOM, the demand signals must flow from a DISCOM to a particular GENCO specifying corresponding demand. These signals which are absent in traditional AGC system, describes the partial demands and are specified by the cpfs and the per unit MW load of a DISCOM. These signals carry information as to which GENCO has to follow a load demanded by the corresponding DISCOM. In the present case of three areas, the scheduled steady state power flow on the tie-line is given as in (17) and the tie line power error is expressed as in (18) which are used to generate the ACE. For n-number power system areas, ACE in i^{th} area is given in (19)

$$\begin{aligned} \Delta P_{tie\,ij}(scheduled) &= \begin{pmatrix} demand\ of\ DISCO\ in\ j^{th}\ area \\ from\ GENCO\ in\ i^{th}\ area \end{pmatrix} \\ &- \begin{pmatrix} demand\ of\ DISCO\ in\ i^{th}\ area \\ from\ GENCO\ in\ j^{th}\ area \end{pmatrix} \end{aligned} \tag{17}$$

$$\Delta P_{tie\,ij}(error) = \Delta P_{tie\,ij}(actual) - \Delta P_{tie\,ij}(scheduled) \tag{18}$$

The error signal is used to generate the respective ACE signals as in the traditional scenario.

$$ACE = B\Delta f + \Delta P_{tie\,error} \tag{19}$$

4.2 System considered for study

The cluster validation for a FLFC is done for a three-area interconnected power system for a step load disturbance of 1% in various areas. The parameters considered for test system to perform the dynamic analysis in frequency deviations are given in Appendix. Three area AGC model shown in Figure 4 is used to validate the clusters of a FLFC in deregulated environment. With a 1% step load change in various areas, the derived clusters are validated for the extracted datasets of input and output of the FLFC with nine rules. The efficacy of the proposed controller is demonstrated on the system considered for study through the step responses of frequency deviations in three individual areas.

4.3 FLC with nine rules as a FLFC

The structure of the FLFC is as shown in Figure 1; the fuzzy inference system is derived for all possible combinations of the three inputs with three membership functions each. The datasets of three inputs are divided into input spaces as shown in Figure 2(a) to derive the relation between the input spaces such that the contributed fuzzy rule base is extracted. From Figure 2(a), it can be clearly observed that the datasets are travelling through six regions. By adapting the procedure mentioned in Section 2, the relation between the input spaces is derived and found that the contributed rule base is with nine rules i.e., 19, 20, 21, 22, 23, 24, 25, 26, 27 and proposed the FLC as a FLFC with nine rules.

4.4 Cluster validation of a FLFC with three rules

As the behaviour of power system is unpredictable for wide range of load variations, the inputs to the controller will be changed for different load conditions. Hence, the input dataset is an unlabeled data and requires proper cluster validity. From Figure 2(a), it can be seen that the max data is clustered in three regions i.e., R_{11}, R_{21}, R_{23}, hence in the present problem the number of clusters ‘c’ is defined as 3 (three) and these three clusters are validated using Section 3. Figure 2 shows the objective function value over number of iterations. For the analysis m is set as 1.25. On optimisation for three fuzzy classes or partitions U matrix is obtained as fuzziest and it assigns every point in input dataset as mentioned in Section 3.2. Hence, it is observed to have a good cluster substructure in input dataset, so the three clusters are identified and validated. Therefore, once the clusters are validated, the number of rules for FLFC is to be selected. It is observed from

Figure 2(b) the three validated clusters fall into three regions i.e., R_{11}, R_{21}, R_{23}. The contributed rules in these three regions are three i.e., Rules 20, 23 and 26 from Table 1. These are derived following the procedure in FCM algorithm. Here the controller is proposed as FCMLFC with three rules.

5 Results and discussions

The robustness of the proposed FCMLFC with minimum rule base is demonstrated on LFC of the three-area interconnected power system for a step load disturbance of 1% and are compared with the performance of FPID and PID controllers (Shayanfar et al., 2006).

5.1 Case 1

Considered that each GENCO in each control area participates in AGC, with area participation factors apf1-apf6 as defined by following:

$$apf1 = 0.5,\ apf2 = 1 - apf1 = 0.5,\ apf3 = 0.5,\ apf4 = 1 - apf3 = 0.5,$$
$$apf5 = 0.6,\ apf6 = 1 - apf5 = 0.4$$

Consider that all the DISCOMs contract with the GENCOs for power as per the below DPM. Suppose that DISCOM3 demands 0.1PU MW power, out of which 0.05PU MW is demanded 0.015PU MW is demanded from GENCO2, 0.02PU MW from GENCO4, and 0.015PU MW from GENCO5. DISCOM3 does not demand any per unit MW from GENCO1, GENCO3, and GENCO6. Then row 2 entries in DPM are easily defined as

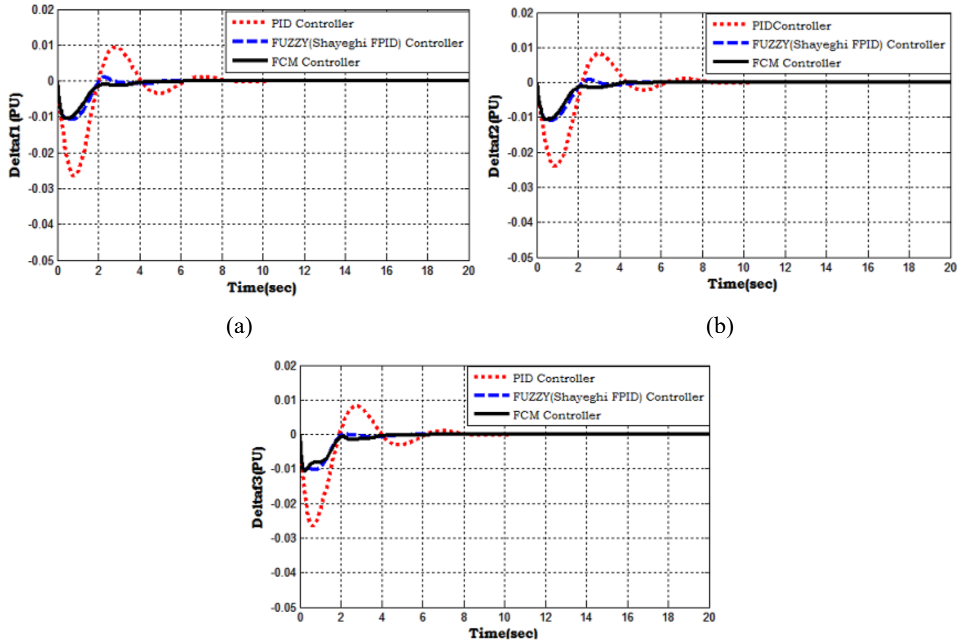
$$cpf_{31} = cpf_{33} = cpf_{36} = 0,\ cpf_{32} = \frac{0.015}{0.1} = 0.15,\ cpf_{34} = cpf_{35} = \frac{0.02}{0.1} = 0.2$$

$$DPM = \begin{bmatrix} 0.3 & 0.25 & 0 & 0.4 & 0.1 & 0.6 \\ 0.2 & 0.15 & 0 & 0.2 & 0.1 & 0 \\ 0 & 0.15 & 0 & 0.2 & 0.2 & 0 \\ 0.2 & 0.15 & 1 & 0 & 0.2 & 0.4 \\ 0.2 & 0.15 & 0 & 0.2 & 0.2 & 0 \\ 0.1 & 0.15 & 0 & 0 & 0.2 & 0 \end{bmatrix}$$

Step increase in load demand in all three areas ΔP_{D1}, ΔP_{D2}, and ΔP_{D3} is applied in this case.

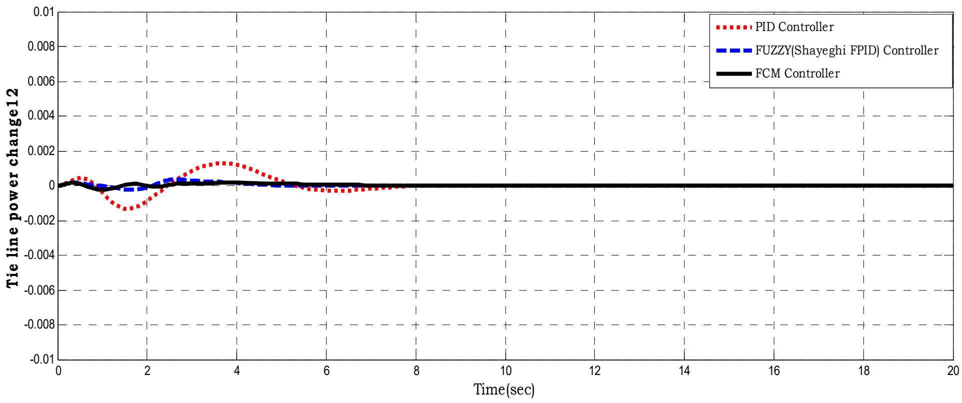
The frequency deviation in area 1 ($\Delta f1$), frequency deviation in area 2 ($\Delta f2$) and frequency deviation in area 3 ($\Delta f3$) are shown in Figure 5 and the inter tie line power deviation between area 1–2 (Tie12) is shown Figure 6.

Figure 5 Frequency deviation in area 1, 2 and 3 with step increase in ΔP_{D1}, ΔP_{D2} and ΔP_{D3}, (a) frequency deviation of area 1 (b) frequency deviation of area 2 (c) frequency deviation of area 3 (see online version for colours)



(c)

Figure 6 Tie line power deviation in areas 1–2 with step increase in ΔP_{D1}, ΔP_{D2} and ΔP_{D3} (see online version for colours)



It can be observed that the proposed FCM controller with minimum rule base has better performance in all responses with respect to overshoot, undershoot and settling time and robustness when compared to fuzzy PID controller and conventional PID controller.

5.2 Case2

The nonlinear nature of speed governor characteristics is approximated for linear analysis. One of the effects of governor dead band is to increase the apparent steady state speed regulation, *R* (Sudha and Vijaya Santhi, 2011). Backlash is the nonlinearity which causes governor dead band and tends to produce continuous sinusoidal oscillations.

Figure 7 Nonlinear turbine model with GRC

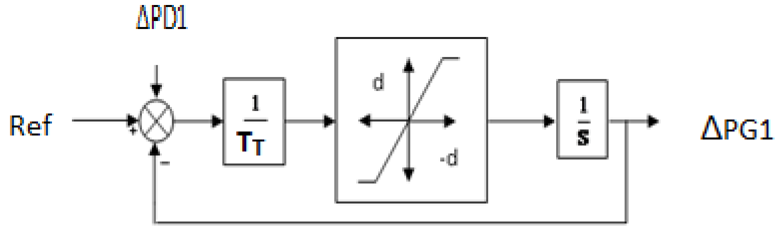
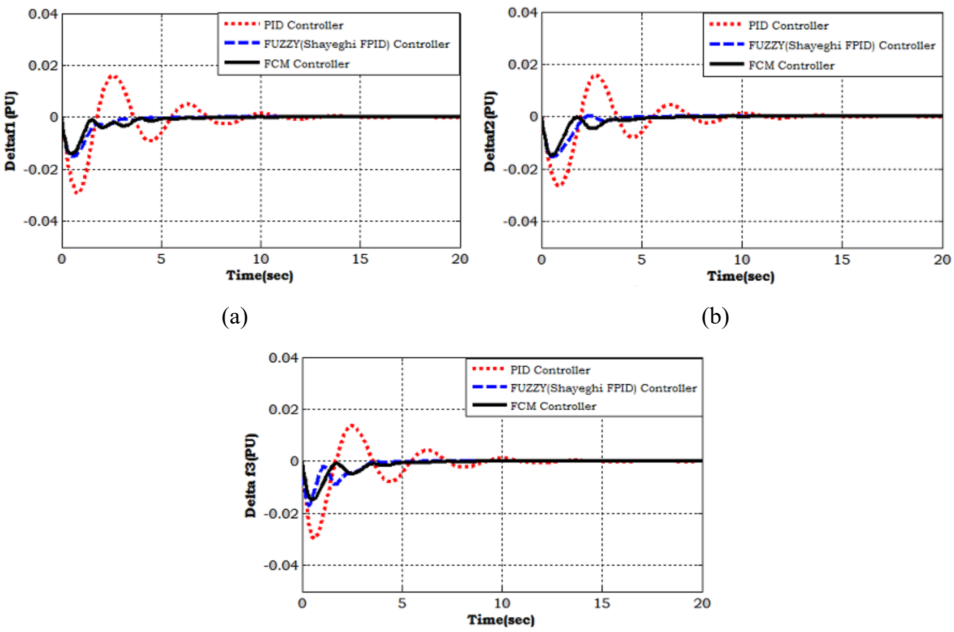


Figure 8 Frequency deviation in area 1, 2 and 3 including GRC with step increase in ΔP_{D1}, ΔP_{D2} and ΔP_{D3}, (a) frequency deviation of area 1 including GRC (b) frequency deviation of area 2 including GRC (c) frequency deviation of area 3 including GRC (see online version for colours)



(a) (b)

(c)

In the present test system, the generating rate constraints (GRC) is set to ±0.1 by using three limiters in each area in Figure 7 within the automatic generation controller to provide the control action within the set limits.

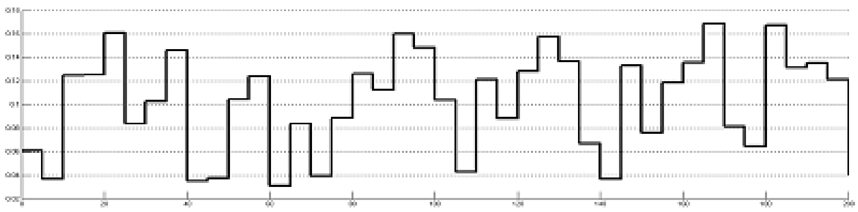
$$\Delta \dot{P}_g \leq 0.1 \text{ p.u MW/min} = 0.0017 \text{ MW/s} \tag{20}$$

Step increase in load demand in all three areas ΔP_{D1}, ΔP_{D2}, and ΔP_{D3} is applied in this case and included GRC. The frequency deviation in area 1 ($\Delta f1$), frequency deviation in area 2 ($\Delta f2$) and frequency deviation in area 3 ($\Delta f3$) are shown in Figure 8. It can be observed that the proposed FCM controller with minimum rule base better performance in all responses with respect to overshoot, undershoot and settling time and robustness when compared to fuzzy PID controller and conventional PID controller.

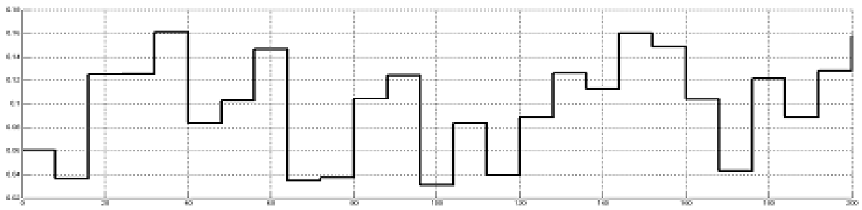
5.3 Case 3

The efficacy of the proposed controller is tested on the system considered for study by having same contracts as in case 1 and the load variations are considered as random, as shown in Figure 9 and ΔP_{D1}, ΔP_{D2}, and ΔP_{D3} continues and large random loading $-0.07 \text{ (pu)} \leq \Delta P_{di} \leq 0.07 \text{ (pu)}$.

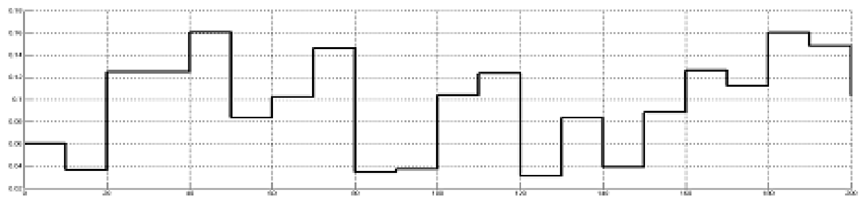
Figure 9 Random load for three control areas in ΔP_{D1}, ΔP_{D2}, ΔP_{D3}



(a)



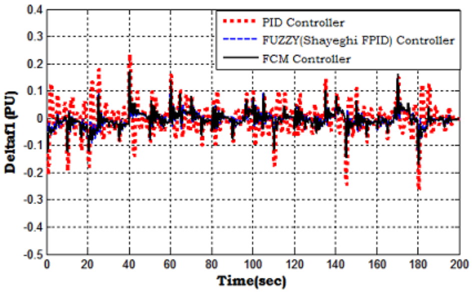
(b)



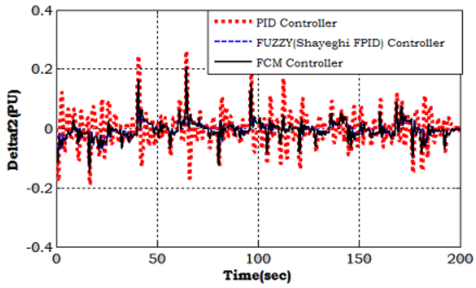
(c)

System dynamic responses in frequency deviation in area 1 (Δ*f*1), frequency deviation in area 2 (Δ*f*2) and frequency deviation in area 3 (Δ*f*3) are shown in Figure 10. Using proposed method frequency deviation quickly reaches zero FCM controller has best performance in all responses. When compared with Fuzzy PID controller and conventional PID controller.

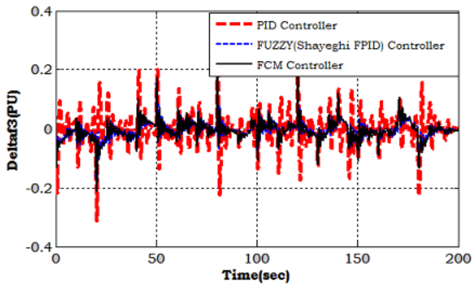
Figure 10 Frequency deviation in area 1, 2 and3 with random loading ΔP_{D1}, ΔP_{D2} and ΔP_{D3}, (a) frequency deviation of area 1 for random loading, (b) frequency deviation of area 2 for random loading (c) frequency deviation of area 3 for random loading (see online version for colours)



(a)



(b)

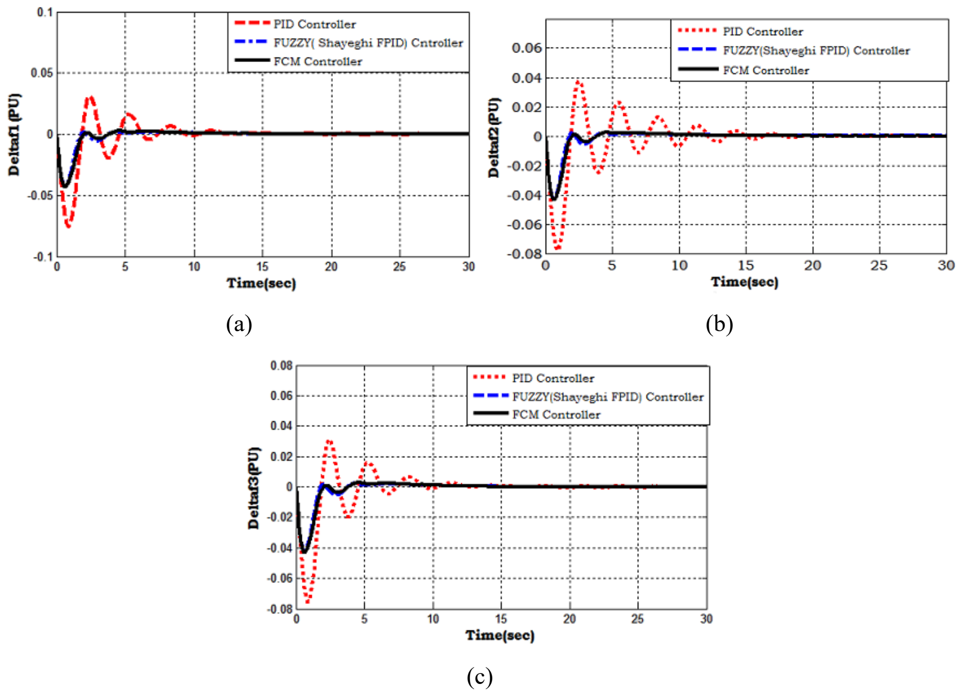


(c)

5.4 Case 4

The efficacy of the proposed controller is tested by considering the practical data relating to the reheat thermal power generating stations for test system in A.P. NTTPS (500 mw, 210 mw) two GENCOs in area 1, KTPS (500 mw, 250 mw) two GENCOs in area 2 and RTPS (210 mw, 210 mw) two GENCOs in area 3 for a step load disturbance of 1% in area 1 (ΔP_{D1}), area 2 (ΔP_{D2}) and area 3 (ΔP_{D3}). The steady state and transient analysis in frequency deviation in area 1 (Δ*f*1), frequency deviation in area 2 (Δ*f*2) and frequency deviation in area 3 (Δ*f*3) are shown in Figure 11 in this case using proposed method frequency deviation quickly reaches zero FCM controller has best performance in all responses when compared to Fuzzy PID controller and conventional PID controller.

Figure 11 Frequency deviation in area 1, 2 and3 under practical case with step increase in ΔP_{D1}, ΔP_{D2} and ΔP_{D3}, (a) frequency deviation of area 1 under practical case (b) frequency deviation of area 2 under practical case (c) frequency deviation of area 3 under practical case (see online version for colours)



The robust performance for the above cases are carried out numerically and comparative results among three controllers such as FCM, fuzzy PID and conventional PID are shown in Table 3.

Table 3 Comparative numerical data analysis of dynamic response in frequency deviation

Case	*Controller*	*Settling time*	*%Maximum overshoot*	*%Under overshoot*
1(Δ*f*1)	PID	10	1.00	2.63
	FPID	5	0.01	1.06
	FCM	5	0.01	1.03
1(Δ*f*2)	PID	10	0.81	2.39
	FPID	5	0.01	1.04
	FCM	5	0.01	1.03
1(Δ*f*3)	PID	10	0.85	2.65
	FPID	5	0.01	1.0
	FCM	5	0.01	1.0
1(Δ*Tie*)	PID	10	1.00	0.128
	FPID	5	0.01	0.03
	FCM	5	0.01	0.01

Table 3 Comparative numerical data analysis of dynamic response in frequency deviation (continued)

Case	*Controller*	*Settling time*	*%Maximum overshoot*	*%Under overshoot*
2($\Delta f1$)	PID	14	1.59	2.99
	FPID	6	0.01	1.49
	FCM	6	0.01	1.39
2($\Delta f2$)	PID	14	1.59	2.99
	FPID	6	0.02	1.46
	FCM	6	0.02	1.44
2($\Delta f3$)	PID	14	1.39	2.91
	FPID	6	0.01	1.67
	FCM	6	0.01	1.45
3($\Delta f1$)	PID	-	23.41	26.26
	FPID	-	17.17	16.6
	FCM	-	17.17	6.6
3($\Delta f2$)	PID	-	24.38	18.78
	FPID	-	15.08	14.57
	FCM	-	15.08	14.57
3($\Delta f3$)	PID	-	31.82	31.17
	FPID	-	24.1	20.63
	FCM	-	24.1	20.63
4($\Delta f1$)	PID	15	3.15	7.28
	FPID	6	0.15	4.26
	FCM	6	0.15	4.26
4($\Delta f2$)	PID	15	3.75	7.74
	FPID	6	0.15	4.18
	FCM	6	0.151	4.18
4($\Delta f3$)	PID	15	3.15	7.28
	FPID	6	0.15	4.26
	FCM	6	0.15	4.26

6 Conclusions

The paper throws a light with an in-depth discussion on design of FLFC with three rules and cluster validation by using FCM to select most contributed rules with an idea to propose better efficacy of a controller in a deregulated environment. This paper successfully tested the efficiency of the proposed controller by incorporating into a three area interconnected thermal power system in deregulated environment, under various operating conditions based on practical data with different nonlinearities. The comparative dynamic response analysis of the results presented and robustness of the proposed FCMLFC controller over FPID and PID controllers under all operating conditions has been proved in this paper. The cluster validation using FCM indentified the most contributed rules. It is concluded that the proposed FCMLFC controller is with three rule base, provides similar control efficiency for wide range of operating conditions even in deregulated environment.

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Appendix

System parameters are shown in Tables 4–7.

Table 4 GENCO parameters

	GENCOs					
	1–1	*1–2*	*2–1*	*2–2*	*3–1*	*3–2*
Rating (MW)	1,000	800	1,100	900	1,000	1,020
TT	0.36	0.42	0.44	0.4	0.36	0.4
TG	0.06	0.07	0.06	0.08	0.07	0.08
R	2.4	3.3	2.5	2.4	2.4	3.3

Table 5 Power system control area parameters

Parameter	*Area 1*	*Area 2*	*Area 3*
Kp	119.04.	71.4	90.9
Tp	19.845	14.28	10.06
B	0.8675	0.785	0.870
Tij		T12 = T13 = 0.545	

Table 6 Practical GENCO parameters

	GENCOs					
	NTTPS-1	*NTTPS-2*	*KTPS-1*	*KTPS-2*	*RTPS-1*	*RTPS-2*
Rating (MW)	500	210	500	250	210	210
TT	0.265	0.192	0.265	0.205	0.192	0.192
TG	0.21	0.20	0.21	0.20	0.20	0.20
R	2.5	2.5	2.5	2.5	2.5	2.5
Kr	0.3	0.28	0.3	0.29	0.28	0.28
Tr	8.05	7.51	8.05	7.68	7.51	7.51

Table 7 Practical power system control area parameters

Parameter	*Area 1*	*Area 2*	*Area 3*
Kp	120	120	100
Tp	10	10	10
B	0.425	0.425	0.425
Tij		T12 = T13 = 0.525	