Fuzzy Load Frequency Controller in Deregulated Power Environment By Principal Component Analysis

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Abstract

Deregulated Load Frequency Control (DLFC) plays an important role in power systems. The main aim of DLFC is to minimize the deviation in area frequency and tie-line power changes. Conventional PID controller gains are optimally tuned at one operating condition. The main problem of this controller is that it fails to operate under different dynamic operating conditions. To overcome that drawback, fuzzy controllers have very much importance. The design of Fuzzy controller's mostly depends on the Membership Functions (MF) and rule-base over the input and output ranges controllers. Many methods were proposed to generate and minimize the fuzzy rules-base. The present paper proposes an optimal fuzzy rule base based on Principal component analysis and the designed controller is tested on three area deregulated interconnected thermal power system. The efficacies of the proposed controller are compared with the Fuzzy C-Means controller and Conventional PID controller.

Keywords

Deregulated Load Frequency Control (DLFC), PID Controller, Fuzzy PID Controller (FPID), Fuzzy C-Means Controller (FCM), Fuzzy Principal component analysis controller (FPCA)

1. Introduction

A power system with deregulated load frequency control may consist of Distribution companies (DISCOMS), Transmission companies (TRANSCOS) and Generation companies (GENCOS). There is a basic difference between the AGC operation in conventional and deregulation power system [1, 16]. After deregulation the vertically integrated utilities (VIU) that own the electrical power generation, transmission and distribution companies amenities provide power at minimum cost to the consumers, after restructuring processes Generation companies (GENCOS), Transmission companies (TRANSCOS), Distribution companies (DISCOMs) and Independent system operators (ISO) are introduced competition in power system[2,3]. Alternative to select among DISCOMs in their own area, while DISCOMs of an area have the choice to have power contracts for transaction of power with GENCOS of the same or other area[5,17].

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Research on the DLFC problem shows that the Fuzzy Proportional Integral Derivative (FPID) controller has been proposed to enhance the performance of deregulated power system load frequency control [10, 11].

The design of a Fuzzy Clustering means (FCM) controller required rule-base from the phase-plane plots of the inputs given to the fuzzy controller. The ‘closed-loop’ trajectory is mapping on position space of the inputs. The clusters are shaped in complete position space of the inputs using Fuzzy C-means. The cluster centers are identified and marked on the phase-plane plot. These are mapping by the ‘closed–loop trajectory’. Hence the necessary rules are recognized and the ‘non-cooperative rules’ are eliminated.

The major disadvantage is Fuzzy C-Means algorithm only detects the data classes with the same super spherical shapes. To overcome the above demerit, a new algorithm is developed fuzzy Principal component analysis (FPCA) involve a geometric procedure that ‘transforms’ a number of correlated variables in to a number of ‘uncorrelated variables’ are called ‘principal components’ [5, 18]. The proposed Fuzzy Principal component analysis Clustering controller with reduced rule base is compared to FCM and Fuzzy PID controller. The above controller test in a three area deregulated load frequency control.

2. MODELING OF THREE AREA LOAD FREQUENCY CONTROL IN Deregulated POWER SYSTEM

The three area load frequency control in deregulated power system environment consists of three power system areas, each power system area with two thermal plants and two DISCOMs as shown in Fig.1. The detailed schematic diagram of three area deregulated power system six GENCO with six DISCOMs as shown in Fig.2.

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 may contract with any GENCO in another control area independently, is known as mutual transaction [18]. These transactions are to be carried out through an independent system operator (ISO).

![Figure.1. Three area load frequency in deregulated power system](image-url)
The main purpose of ISO is to control system operator in all GENCOs and DISCOMs, like Automatic Generation Control. Any DISCOM in a deregulated environment will have the free to purchase power at competitive price from different GENCOs, which can or cannot have contract with the won area when the ‘DISCOM’ [9]. In the present paper for the load frequency control GENCO–DISCOM contracts are represented with ‘DISCOM participation matrix’ (DPM). DPM effectively provides the participation of a DISCOM in contract with a GENCO. The concept of ‘DISCOM Participation Matrix’ (DPM) is used to express the possible contracts. The number of rows and columns of DPM matrix is equal to the total number of GENCOs and DISCOMs in the overall power system, respectively. Each element of the DPM is a fraction of total load power contracted by a DISCOM from a GENCO and is called a contract participation factor (cpf). The total of all the elements in a column in ‘DPM’ is unity.

\[
\begin{bmatrix}
    \text{cpf}_{11} & \text{cpf}_{12} & \text{cpf}_{13} & \text{cpf}_{14} & \text{cpf}_{15} & \text{cpf}_{16} \\
    \text{cpf}_{21} & \text{cpf}_{22} & \text{cpf}_{23} & \text{cpf}_{24} & \text{cpf}_{25} & \text{cpf}_{26} \\
    \text{cpf}_{31} & \text{cpf}_{32} & \text{cpf}_{33} & \text{cpf}_{34} & \text{cpf}_{35} & \text{cpf}_{36} \\
    \text{cpf}_{41} & \text{cpf}_{42} & \text{cpf}_{43} & \text{cpf}_{44} & \text{cpf}_{45} & \text{cpf}_{46} \\
    \text{cpf}_{51} & \text{cpf}_{52} & \text{cpf}_{53} & \text{cpf}_{54} & \text{cpf}_{55} & \text{cpf}_{56} \\
    \text{cpf}_{61} & \text{cpf}_{62} & \text{cpf}_{63} & \text{cpf}_{64} & \text{cpf}_{65} & \text{cpf}_{66}
\end{bmatrix}
\] (1)

Where

\[
\text{cpf}_{ij} = \frac{j^{th} \text{DISCO power demand out of } i^{th} \text{GENCO in p.uMW}}{j^{th} \text{DISCO total power demand in p.uMW}}
\] (2)

Whenever a load demanded by a DISCOM1 changes, it is observed as a local load change in the area1, which is similar with other areas corresponds to the local loads \(\Delta P_{D1}, \Delta P_{D2}, \Delta P_{D3}\). 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. Each area two GENCOs, ‘Area Control Error’ (ACE) signal has to be “distributed” among them. The factor that distributes ‘ACE participation factors’ (apf)

Therefore

\[
\sum_{k=1}^{n} a_{ pfk} = 1
\] (3)

Where total number of ‘plants’ are n

The each ‘particular’ set of ‘GENCOs’ are invented to follow the ‘load demanded’ by a DISCOM, the demand signals must flow from a DISCOM to a particular GENCO specifying ‘corresponding’ load demands. These signals which are absent in traditional AGC system describes the partial demands and are specified by the cfps and the per unit MW load of a DISCOM. The signals take information as to which plants have to track a ‘load demanded’ by which ‘DISCOM’. In the present case of three areas, the scheduled steady state power flow on the tie-line is given as in (4) and the tie line power error is expressed as in (5) which is used to generate the area control error (ACE). For n-number power system areas, Area Control Error in 1\(^{th}\) area is given in (6)
\[
\Delta P_{\text{tie}_ij} \text{ (scheduled)} = \\
\text{(demand of DISCO in } j^{\text{th}} \text{ area from GENCO in } i^{\text{th}} \text{ area)} \\
- \text{(demand of DISCO in } i^{\text{th}} \text{ area from GENCO in } j^{\text{th}} \text{ area)}
\]

(4)

\[
\Delta P_{\text{tie}_ij} \text{ (error)} = \Delta P_{\text{tie}_ij} \text{ (actual)} - \Delta P_{\text{tie}_ij} \text{ (scheduled)}
\]

(5)

The traditional scenario ‘error signal’ is use to make the respective ‘ACE signals’ as in the.

\[
\text{ACE} = B\Delta f + \Delta P_{\text{tie error}}
\]

(6)

For our case

NGENCO = 6 = Total number of generation companies

NDISCO = 6 = Total number of distribution companies

Figure 2. Three area deregulated LFC
3. DESIGN OF FUZZY LOGIC PID (FPID) CONTROLLER

The general model of Fuzzy PID normal Controller and it mainly four important components are Fuzzification module, Inference mechanism, Knowledge base and defuzzification module.

3.1. Fuzzification Module:

In primary operation is import is fuzzification which include convert all the range of input data with output of the FLC their corresponding data [12, 13]. The next performance procedure is dividing the respective input keen on suitable linguistic variables these variables in fuzzification module depend on triangle shape of the Membership functions (MF).

3.2. Fuzzy Inference mechanism:

Interface mechanism plays a important role in designing FLC. The membership functions obtained in first step are combined to acquire the firing strength of individual rule [24, 25]. Each rule characterizes the control goal and control strategy of the field experts by means of a set of Fuzzy control rules [8, 14]. Then depending on firing strength, the consequent part of each qualified rule is generated.

3.3. Knowledge base:

The knowledge base of an FLC consists of a database, whose basic function is to provide, the necessary information for the proper functioning of the ‘fuzzification module’, the inference engine and the ‘de-fuzzification module’. The necessary information includes:

a) ‘Fuzzy membership’ representing the meaning of the ‘linguistic variables’ of the process status and the ‘control output variables’.

b) Physical domains and their normalized counter-parts together with the normalization (scaling) factors.
3.4. Defuzzification module:

The following are the functions of the Defuzzification module:

a) It converts the set of modified control output values into a non-fuzzy control output.
b) It performs an output de-normalization which maps the range of values of fuzzy sets to the normal area.

The commonly used strategies for defuzzification are (i) max criterion (ii) the mean of maximum and (iii) the center of areas. Approach generates the ‘center of gravity’ of the opportunity distribution of a ‘control action’.

\[
U = \frac{\sum \{\text{Membership value of input} \times \text{output corresponding to the membership value of input}\}}{\sum \{\text{membership value of input}\}}
\]

\[
U = \frac{\sum v(A_i, B_i)}{\sum \mu(A_i, B_i)}
\]

3.5. Design of three input MF FPID Controller:

Design of FPID Controller similar to PID controller as below fig 4.

![Figure 4: basic model FPID controller](image)

Three variables \( \delta, \dot{\delta}, \ddot{\delta} \) are used as input signals. The coefficients \( K_p, K_d, K_i \) which are called Fuzzy variables, transform the scaled real values to required values in decision limit. The ‘output signal’ \( K_u \) is inject to the ‘summing point’. The normalized inputs of the proposed controllers namely DE, E, and DEE are equal to \( K_p \delta, K_i \delta, K_d \ddot{\delta} \) respectively. The three similar fuzzy sets defining the three inputs of the proposed FLCPID controller are given by equation (8). The inputs of the fuzzy sets considered are shown in figure .5 and the MF of these are defined by \( \mu_p(\cdot), \mu_n(\cdot) \) hand \( \mu_z(\cdot) \) or \( \mu_1(\cdot), \mu_{-1}(\cdot) \) and \( \mu_0(\cdot) \)

\[
K_p \delta = K_d \ddot{\delta} = K_i \delta = \{N(\text{Negative}), Z(\text{Zero}), P(\text{Positive})\}
\]
Let the number of linguistic variables and their values are the inputs and their MF is identical. If the members of the input fuzzy set N,Z and P are \(X_{-1}(\cdot), X_0(\cdot), X_1(\cdot)\) respectively, then the output function is derived using the following control rules, where \(i, j, k\) can take any value from \((-1,0,+1)\).

**IF** \(DE\) is \(x_i\) and \(E\) is \(x_j\) and \(DEE\) is \(x_k\) **THEN** output is \((-i+j+k)\)

The above fuzzy rule is called a linear control rule because the linear function is employed to relate the indices of the input fuzzy variables sets to the index of the linguistic variables output fuzzy set. Based on this concept the rules framed.

### 3.6. FPID Controller Rules

FPID control rules are linear, the number of ‘membership functions’ of the fuzzy output place will be equal to \((3N - 2)\) for \(N \geq 3\), The number of membership functions \(N\) of each input. In the proposed case \(N=3\), hence the output fuzzy set has seven membership functions defined as follows:

\[
U = \{NB(negative \ big), NM(negative \ medium), NS(negative \ small) \}
\]

\[
\{Z(zero)\}
\]

\[
\{PB(positive \ big), PS(positive \ small), PM(positive \ medium)\}
\]

The triangular membership functions as in Fig (5) are considered and partitioned within the UOD in the range \([-1, +1]\) for the outputs. The mathematical model of membership function is given as follows:

![Figure 5. Membership-Functions Outputs](image)

The portion of the ‘Membership-Functions’ output should be symmetrical about its essential value and the ‘shape’ of every the members of ‘Membership-Functions’ should be same \([14, 20]\). The decisions in fuzzy logic based approach are made by forming series of rules which relate the inputs to outputs by IF-THEN statements \([21]\). In this case the number of control rules to cover all the possible combinations of the three membership functions of each input variable is \(3 \times 3 \times 3(27)(4)\). These rules are composed as below table1.
Table 1. 27 Rules for three input membership functions

<table>
<thead>
<tr>
<th>Rule</th>
<th>DEE</th>
<th>DE</th>
<th>E</th>
<th>Out put</th>
<th>Rule</th>
<th>DEE</th>
<th>DE</th>
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<th>Out put</th>
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<td>P</td>
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<td>PM</td>
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<td>Z</td>
<td>NM</td>
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<td>PM</td>
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4. Design Of FCM Controller

Fuzzy control normal system requires characterization of the relation between state spaces and the rules associated with the transient system under control this relation is based on the relative influence of every rule of the rule base on the direct action produced by ‘fuzzy inference engine’ [6].

A closed loop trajectory can be mapped on the position space [19]. Linguistic trajectory is formed by the series of rules obtained ‘according’ to the arrange in which they are fired forms. This corresponds to a certain system trajectory [22]. This provides strategy to attain the necessary rule-base starting the ‘phase-plane’ plots of the inputs given to the fuzzy controller [23]. The space of the inputs is mapped on position ‘closed-loop trajectory’. The formed clusters are in complete location space of the inputs using Fuzzy C-means. The cluster centers are recognized and marked on the phase-plane plot. The closed–loop ‘trajectory’ with these is mapped. Hence the ‘non-cooperative’ rules are deleted and the necessary rules are identified.

4.1 Design procedure for FCM Controller

1) The Fuzzy controller is designed normally with 27 rules.
2) The ‘Fuzzy C-Means controller’ is tuned to the same as fuzzy controller.
3) From the input space of fuzzy controller the ‘phase-plane’ plot is obtained.
4) FCM algorithm using input space is ‘divided’ into ‘clusters’ and the centers of ‘cluster’ are recognized.
5) The series of rules of the normal ‘fuzzy controller’ is great imposed onto the ‘phase-plane’ plot of the ‘input space’ with ‘cluster centers’ below fig.6.
6) Hence the ‘non-cooperative’ rules are deleted and the necessary rules are ‘identified’ below table2.
Fig. 6. Phase plane plot to identify required rules

Table 2. Rules for three-input membership functions for FCM Controller

<table>
<thead>
<tr>
<th>Rule</th>
<th>DEE</th>
<th>E</th>
<th>DE</th>
<th>Output</th>
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<td>P</td>
<td>NS</td>
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5. Design of Fuzzy Principal Component Analysis (FPCA) Controller

The major disadvantage is Fuzzy C-Means algorithm only detects the data classes with the same super spherical shapes. To overcome the above demerit new algorithm is developed fuzzy Principal component analysis (FPCA) involves a mathematical procedure that transforms a number of (possibly) correlated variables into a (smaller) number of uncorrelated variables are called principal components [5]. The first principal component accounts for as much of the variability in the data as possible and each succeeding component accounts for as much of the remaining variability as possible [10]. The main objectives of FPCA are:

1) New meaningful fundamental variables Identify
2) Determine or to decrease the ‘dimensionality’ of the data set
3) The protrusion of correlated ‘high-dimensional’ data onto a ‘hyper-plane’

There are several equivalent ways of deriving the principal components mathematically. The ‘simplest’ one is by discovery the ‘projections’ which large the ‘variance’ [11]. The initial ‘principal component’ is the path in quality space along which ‘projections’ have the biggest variance. The next ‘principal component’ is the path which large ‘variance’ among all ‘directions’ orthogonal to the initial. The $n^{th}$ element is the ‘variance-maximizing’ direction ‘orthogonal’ to the before $(n-1)$ components. There are $p$ principal components in all. Relatively
than large variance, it power sound more promising to appear for the ‘projection’ with the least regular (‘mean-squared’) distance between the innovative ‘vectors’ and their ‘projections’ on to the ‘principal components’. This twist out to be corresponding to large the variance. Which the data points are projected and data is clustered with PCA algorithm identifies minimum number of contributed rules.

5.1 Proposed FPCA Algorithm:

1) The common Fuzzy controller is designed normally with 27 rules
2) The ‘FPCA controller’ is tuned to the same as ‘fuzzy controller’.
3) It is the best possible linear design for ‘compressing’ a set of large ‘dimensional’ vectors into a set of lesser ‘dimensional’ vectors and then reconstructing
4) Form the matrix of squares and products of the features $Z^T Z$, where scaled report of the ‘matrix’ $X$ & $Z$ is the ‘centered’.
5) The next ‘principal component’ is the direction ‘orthogonal’ to the initial component with the large variance. Since it is ‘orthogonal’ to the initial ‘eigenvector’, their ‘projections’ resolve be ‘uncorrelated’ and the ‘principal components’ are ‘uncorrelated’ with all other
6) The ‘principal components’ are designed as $P = X E$, where $X$ is the ‘original data matrix’ of order $n \times j$, of ‘principal components’ $P_1, P_2, P_3, P_4…$
7) The input space is divided into Principal components using PCA and the Principle components are identified using fig.7.
8) The sequence of rules of the unusual fuzzy controller is recognized by using ‘Principal components’.
9) Hence the ‘non-cooperative’ rules are deleted and the necessary rules are ‘identified’ below table3.

Figure 7.Clusters using principal component analysis
Table 3. Rules for three-input membership functions for FPCA Controller

<table>
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<tr>
<th>Rule</th>
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6. RESULTS AND DISCUSSIONS

The robustness and efficacy of the proposed FPCA controller with minimum rule base is tested in a three-area interconnected deregulated power environment for various operating conditions and compared with performance of FCM and PID controller.

**Case1:** In this case each GENCO in each control area participates in AGC, with area participation factors $apf_1$-$apf_6$ as defined by the following:

$$apf_1 = 0.5, apf_2 = 1 - apf_1 = 0.5, apf_3 = 0.5, apf_4 = 1 - apf_3 = 0.5, apf_5 = 0.6, apf_6 = 1 - apf_5 = 0.4,$$

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 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

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

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

Step increase in load demand in all three areas $\Delta PD_1, \Delta PD_2,$ and $\Delta PD_3$ is applied in this case. The frequency deviation in area1 ($\Delta f_1$) is shown in Fig.8, frequency deviation in area2 ($\Delta f_2$) is shown in Fig.9, and frequency deviation in area3 ($\Delta f_3$) is shown in Fig.10. It can be observed that the proposed FPCA controller with minimum rule base has better performance in all responses with respect to overshoot, undershoot and settling time and robustness when compared to FCM controller and PID controller.
Figure 8. Frequency deviation in area 1 with step increase in $\Delta PD_1$, $\Delta PD_2$ and $\Delta PD_3$.

Figure 9. Frequency deviation in area 2 with step increase in $\Delta PD_1$, $\Delta PD_2$ and $\Delta PD_3$.

Figure 10. Frequency deviation in area 3 with step increase in $\Delta PD_1$, $\Delta PD_2$ and $\Delta PD_3$. 

Fig. 10. Frequency deviation in area 3 with step increase in $\Delta PD_1$, $\Delta PD_2$ and $\Delta PD_3$. 

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Case 2:

In this case same as the case 1 but included the Generator Rate Constraints (GRC) the rate of change in the power generating is to be maintained at a specified maximum limit. In regulate to consider effect of the GRC into account a step load disturbance of 1% in area 1, area 2 and area 3, the MATLAB simulation power system model of a non reheating turbine is changed through a nonlinear model of Fig. 11 with saturation element \( d = \pm 0.1 \) P.U/minute is considered. For the present test system, the generating rate constraints is set to \( \pm 0.1 \) by using each limiters in each GENCO within the AGC controller to provide the control action within set limits. It can be observed that the proposed FPCA controller with minimum rule base has better performance in all responses with respect to overshoot, undershoot and settling time and robustness when compared to FCM controller and PID controller are tested deregulated power system with including GRC. The outcome in above case are given in Fig 12-14.

Figure 11. Nonlinear turbine model with GRC

Figure 12. Frequency deviation in area 1 including GRC with step increase in \( \Delta PD_1, \Delta PD_2 \) and \( \Delta PD_3 \)
Figure 13. Frequency deviation in area 2 including GRC with step increase in $\Delta PD_1$, $\Delta PD_2$ and $\Delta PD_3$

Figure 14. Frequency deviation in area 3 including GRC with step increase in $\Delta P_{D1}$, $\Delta P_{D2}$ and $\Delta P_{D3}$

Case 3:
In this case the contract same as the case 1. Also load demand for each DISCO is considered 0.1 pu, the bounded variable step load changes in the a load change as un contracted demand in area 1, area 2 and area 3 (Fig 15) appears in all control areas where

$$-0.07(\text{pu}) \leq \Delta P di \leq 0.07(\text{pu})$$

The purposed for this toward check the robustness load variations up 40% deregulated power system of above It can be observed that the proposed FPCA controller with minimum rule base has better performance in all responses with respect to overshoot, undershoot and settling time and robustness when compared to FCM controller and PID controller. against parametric uncertainties and variable large load changes. $\Delta pd_1$, $\Delta pd_2$ and $\Delta pd_3$ (fig 22-25). The results in this case are given in Fig 16-18
Figure 15. Random load for three control areas in $\Delta P_{D1}$, $\Delta P_{D2}$, $\Delta P_{D3}$

Figure 16. Frequency deviation in area 1 with Random loading $\Delta P_{D1}$, $\Delta P_{D2}$ and $\Delta P_{D3}$

Fig. 17. Frequency deviation in area 2 with Random loading $\Delta P_{D1}$, $\Delta P_{D2}$ and $\Delta P_{D3}$
Figure 18. Frequency deviation in area 3 with Random loading $\Delta P_{D1}$, $\Delta P_{D2}$ and $\Delta P_{D3}$

Table 3. Numerical analysis of above results

<table>
<thead>
<tr>
<th>Case</th>
<th>Controller</th>
<th>Settling Time (sec)</th>
<th>Maximum overshoot</th>
<th>Under overshoot</th>
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<td>0.13</td>
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<td>0.02</td>
<td>0.11</td>
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<td>4.5</td>
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<td>PID</td>
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<td>0.02</td>
<td>0.11</td>
</tr>
<tr>
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6. CONCLUSION

In this paper a new controller Fuzzy Principal component analysis controller (FPCA) is design minimization of fuzzy rules for load frequency control deregulated power system. The minimum rules indentify by using principal component analysis locus and identify the clusters centers in hyper-plane and converts in to the rules for FPCA controller. The FPCA controller tested for load frequency three area deregulated power system with minimum rules better performance of FCM Controller. The simulation results are signify the FPCA Controller is good performance in all operating conditions and mainly consider settling time, percentage of maximum over shoot, and under shoot. The numerical analysis show that  FPCA Controller as better performance as compare to FCM and PID Controller.

REFERENCES


