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NERC's control performance standards based load frequency controller for a multi area deregulated power system with ANFIS approach

Abhijith Pappachen *, A. Peer Fathima

School of Electrical Engineering, VIT University, Chennai 600127, Tamil Nadu, India

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ABSTRACT

This paper presents the design of a North American Reliability Council (NERC) standards BAL-001-2 based Adaptive Neuro-Fuzzy Interface System (ANFIS) controller for multi-area deregulated power system under different contract scenarios. The proposed controller is tested on the Indian regional grid system and its control performance standards are compared with the conventional PID controller and ANFIS controller. The major objectives are (i) To find a suitable control for mitigating the diverse LFC problems in a deregulated power system (ii) to comply with the NERC control performance standards which are CPS1, CPS2 and BAAL, and (iii) to reduce the wear and tear of the generating units. Dynamic modelling of controllers, test system and simulation studies are performed using MATLAB/Simulink environment. The simulation results validate that the NERC standards based ANFIS controller is one of the best controller for the four area Indian regional grid under deregulated environment.

1. Introduction

Load frequency control is one of the major control problems in an interconnected power system design and operation. In an interconnected power system, LFC has two important objectives; to maintain the frequency of each area within the specified limit and to control the inter area tie-lines power exchanges within the scheduled values [1–4]. LFC is becoming more significant in recent times due to the size and complexity of entire power system network.

In a conventional power system, the power generation, transmission, distributions are owned by a single entity called vertically integrated utility (VIU). VIU supplies power to their consumers at a specified rate. After restructuring, the role of VIU is carried out by different market players like Generating companies (GENCOs), Transmission companies (TRANSCOs), Distribution companies (DISCOs) and Independent System Operators (ISO) [2,5–8]. These market players control the generation and load demand by keeping the entire power system stable under a highly competitive and distributed control environment. However, the critical function of LFC is still an ongoing challenge in the deregulated power system [9–11]. Due to lack of proper controller design in a deregulated power system, the instability may spread to other control areas and may lead to a severe system black out. To overcome these situations, numerous studies are conducted about various LFC issues in a deregulated power system.

In order to improve the dynamic responses of the power system network, various control techniques like artificial neural network (ANN), fuzzy logic control, genetic algorithm (GA), particle swam optimization (PSO) etc are also applied for controlling the output response of the entire system [5,12–17]. All these control techniques continuously track the load fluctuations and adjust the turbine governor set points as soon as possible to bring back the system to its stable operating region [5–8,14]. However, continuous tracking of the load fluctuations create unnecessary wear and tear on governor's and turbines moving parts. It will decrease the life span and increase the maintenance cost.

In this paper, the NERC's real power balancing control performance standard BAL-001-2 based ANFIS controller for load frequency control applications in a deregulated power system under three different contract scenarios are discussed. An ANFIS technique based Load Frequency controller whose rules are designed such that its control performance is in compliance with NERC's standards viz. CPS1, CPS2 and BAAL and also reduce the wear and tear of generating units' equipments. In this deregulated control structure, PID controller whose rule base is designed such that its control parameter is used to reduce the high frequency movement of the speed governor's equipments when the control area has high compliance with NERC's standards. When the compliance is low, the control parameter is raised up to the normal value. The

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* Corresponding author.
E-mail address: abhijith.pappachen2013@vit.ac.in (A. Pappachen).

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Nomenclature

NERC	North American reliability council	ISO	independent system operator
BAAL	balancing authority ACE limit	VIU	vertically integrated utility
FTL	frequency trigger limit	DPM	DISCO participation matrix
f	system frequency	CPS	control performance standard
B	frequency bias constant	GA	genetic algorithm
R	governor speed regulation parameter	T_P	power system equivalent time constant
ε	targeted frequency bound	T_G	governor time constant
LFC	load frequency control	T_T	turbine time constant
ACE	area control error	T_{12}	tie-line synchronizing coefficient between areas
GENCO	generation company	ΔP_{tie12}	net tie-line power flow
DISCO	distribution company	ΔP_c	speed changer response
TRANSCO	transmission company		

proposed methodology is tested using an Indian Regional grid system. The Test system parameters are taken from the Indian regional grid websites.

2. Multi area deregulated power system analyzed

The four area deregulated power system as shown in Fig. 1 consists of four distinct control areas and each area having one GENCO and one DISCO. Area-1 consists of hydro GENCO and the remaining areas having thermal GENCOs. In general, a deregulated power system has several numbers of GENCOs and DISCOs and any DISCO may power contract with any GENCOs in other area independently [2–8]. Under open access scenario, DISCOs have the freedom to purchase MW power from any GENCOs independently. The various types of contract between GENCOs and DISCOs are represented by the Distribution Participation Matrix (DPM) [2]. The *n*th area power system can be represented through DPM as follows

$$DPM = \begin{bmatrix} cpf_{11} & cpf_{12} & \dots & cpf_{1n} \\ cpf_{21} & cpf_{22} & \dots & cpf_{2n} \\ \vdots & \vdots & \dots & \vdots \\ cpf_{31} & cpf_{32} & \dots & cpf_{nm} \end{bmatrix} \tag{1}$$

The number of rows and columns in a DPM represents the number of GENCOs and DISCOs respectively and each entry in the DPM is noted as contract participation factor (*cpf*), which represents the fraction of total power contracted between GENCOs and DISCOs [4–6]. The sum of all the entries in a column matrix (corresponding to one DISCO) must be unity. ie.,

$$\sum_{i=1}^{nGENCO} cpf_{ij} = 1; \quad \text{for } j = 1, 2, \dots nDISCO \tag{2}$$

The scheduled steady state power flow through the tie-lines is expressed as

$$\begin{aligned} \Delta P_{Tieij,scheduled} = {} & (Demand\ of\ DISCOs\ in\ Area\text{-}i\ from\ GENCOs\ in\ Area\text{-}j) \\ & - (Demand\ of\ DISCOs\ in\ Area\text{-}j\ from\ GENCOs\ in\ Area\text{-}i) \end{aligned} \tag{3}$$

From Eq. (2), mathematically modified $\Delta P_{tie12,scheduled}$ is written as

$$\Delta P_{Tie12,scheduled} = \sum_{i=1}^{2}\sum_{j=3}^{4} cpf_{ij}\Delta P_{Lj} - \sum_{i=3}^{4}\sum_{j=1}^{2} cpf_{ij}\Delta P_{Lj} \tag{4}$$

Similarly scheduled tie-line power flow in other control areas is also defined by these equations.

In general, actual value of tie line power flow is

$$\Delta P_{Tie,ij,actual} = \frac{T_{ij}}{s}(\Delta\omega_i(s) - \Delta\omega_j(s)) \tag{5}$$

From Eq. (5) actual value of tie-line power flow between area-1 and area-2 is expressed as

$$\Delta P_{Tie12,actual} = \frac{T_{12}}{s}(\Delta\omega_1(s) - \Delta\omega_2(s)) \tag{6}$$

error in tie-line power flow between area-1 and area-2 is

$$\Delta P_{Tie12,error} = \Delta P_{Tie12,actual} - \Delta P_{Tie12,scheduled} \tag{7}$$

Under steady state condition, $\Delta P_{Tie12,error}$ vanishes when the actual tie line power flow reaches the scheduled tie line power flow.

In general, the Area Control Error (ACE) signal generated by the respective areas is defined as

$$ACE_i = B_i\Delta\omega_i + \Delta P_{Tie12,error}, i = 1, 2, \dots, 4 \tag{8}$$

It is noted that under steady state condition, the desired power generation (ΔP_{Gi}) of *i*th control area can be expressed as the sum of total contracted and uncontracted load demand of DISCOs coming under *i*th control area.

$$\Delta P_{Gi} = \sum_j cpf_{ij}\Delta P_{Lj} - apf\sum \Delta P_{UCi} \tag{9}$$

where ΔP_{Lj} the total is demand of *j*th DISCO and ΔP_{UCi} is the uncontracted demand.

3. NERC's real power balancing control performance standards

The NERC is a non-profit corporation was formed on June 1, 1968, by the electric utility industry to promote the reliability and adequacy of bulk power transmission in the electric utility systems of North America. For smooth and reliable operation of the entire power system, every year NERC produces different control performance standards.

In multi area power system network, the different control areas are interconnected through tie lines for maintaining the power balance between each other [18–24]. The energy balance is maintained by the Area Control Error (ACE) signal which is given as:

$$ACE_i = \Delta P_{tie} - 10B_i\Delta F \tag{10}$$

where ΔF is the interconnected frequency error and B_i is the frequency bias setting, expressed in MW/0.1 Hz.

In February 1997, North American Reliability Council (NERC) proposed a new real power balancing control performance standards called BAAL-001-1. In this, they implemented two new control performance standards named as CPS1 and CPS2 to evaluate the control area performance in an interconnected power system [22–24]. Each control area is required to evaluate the control area

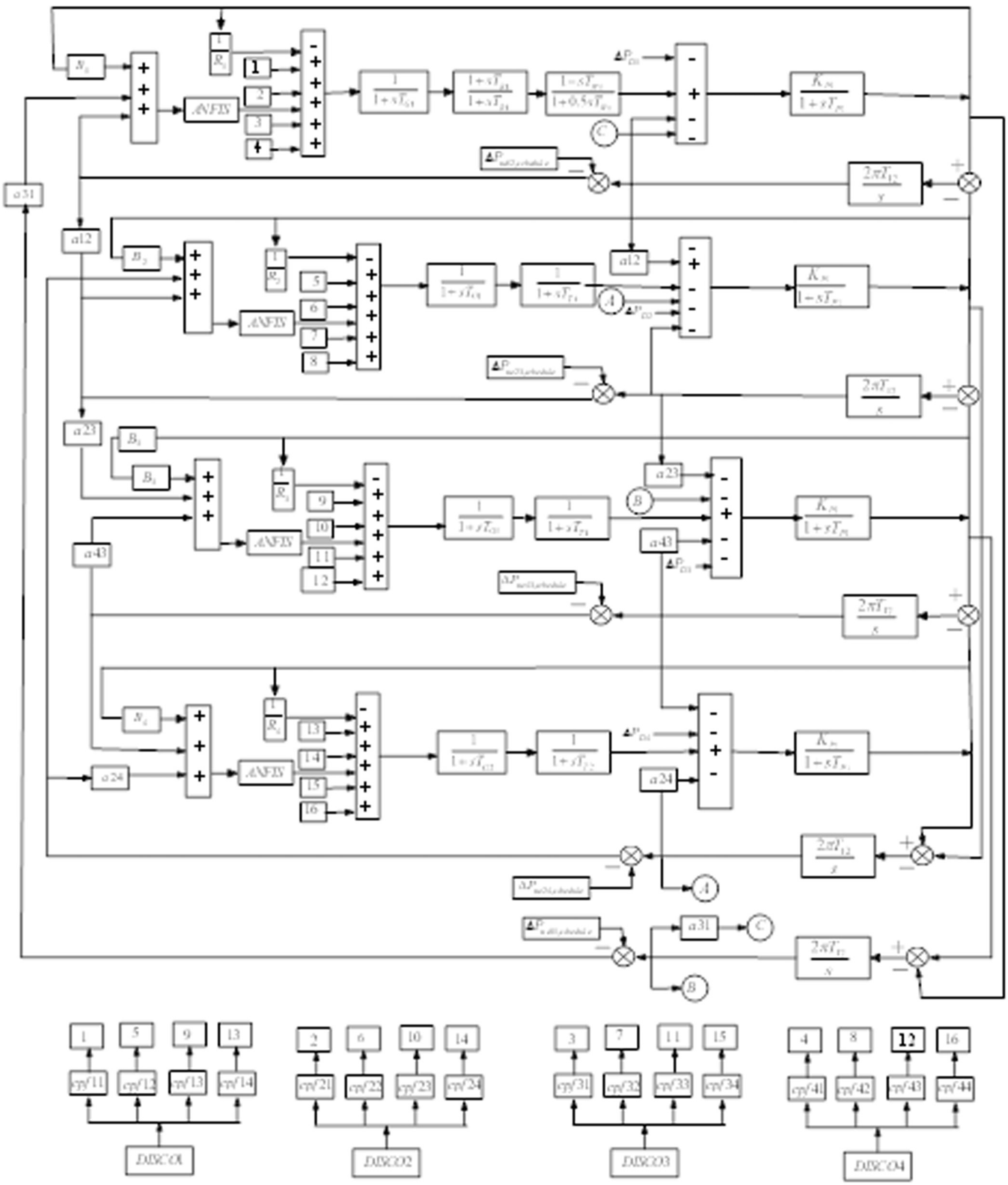

Fig. 1. MATLAB/Simulink model of a four area deregulated power system model.

performance and report its compliance with CPS1 and CPS2 to NERC at the end of every month [19–21,26]. But in 2013, BAL-001-2 standard came and it retains the CPS1, but proposes a new measure BAAL. Details are explained below.

3.1. BAL-001-2 – real power balancing control performance standard

The purpose of the proposed standard BAL-001-2 is to maintain the interconnected system frequency within its prescribed limits.

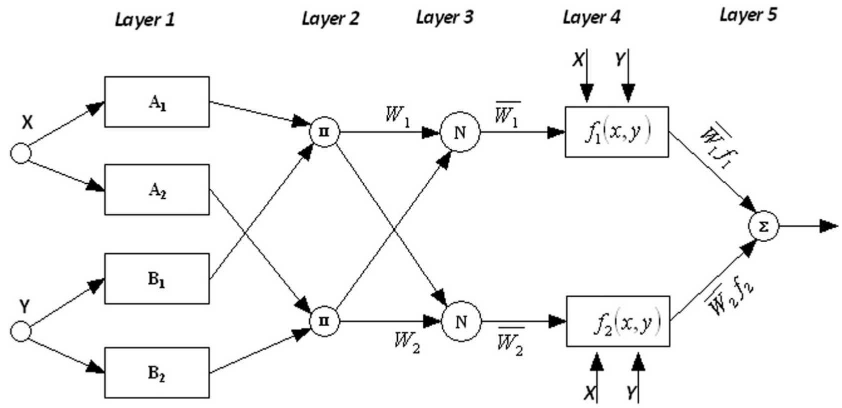

Fig. 2. ANFIS structure.

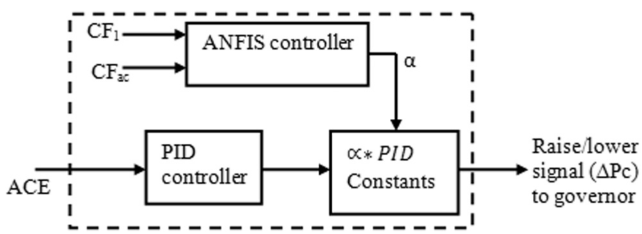

Fig. 3. ANFIS rule based load frequency control.

The draft standard defines Balancing Authority ACE Limit (BAAL) and requires the balancing Authority (BA) to balance its resources and demand in real-time so that its clock-minute average of its area control error does not exceed its BAAL for more than 30 consecutive clock-minutes. In BAL-001-2, control performance standard CPS1 is retained and CPS2 is modified by a new measurement called BAAL [23].

The main modifications in the BAL-001-2 real power control performance standard are explained below.

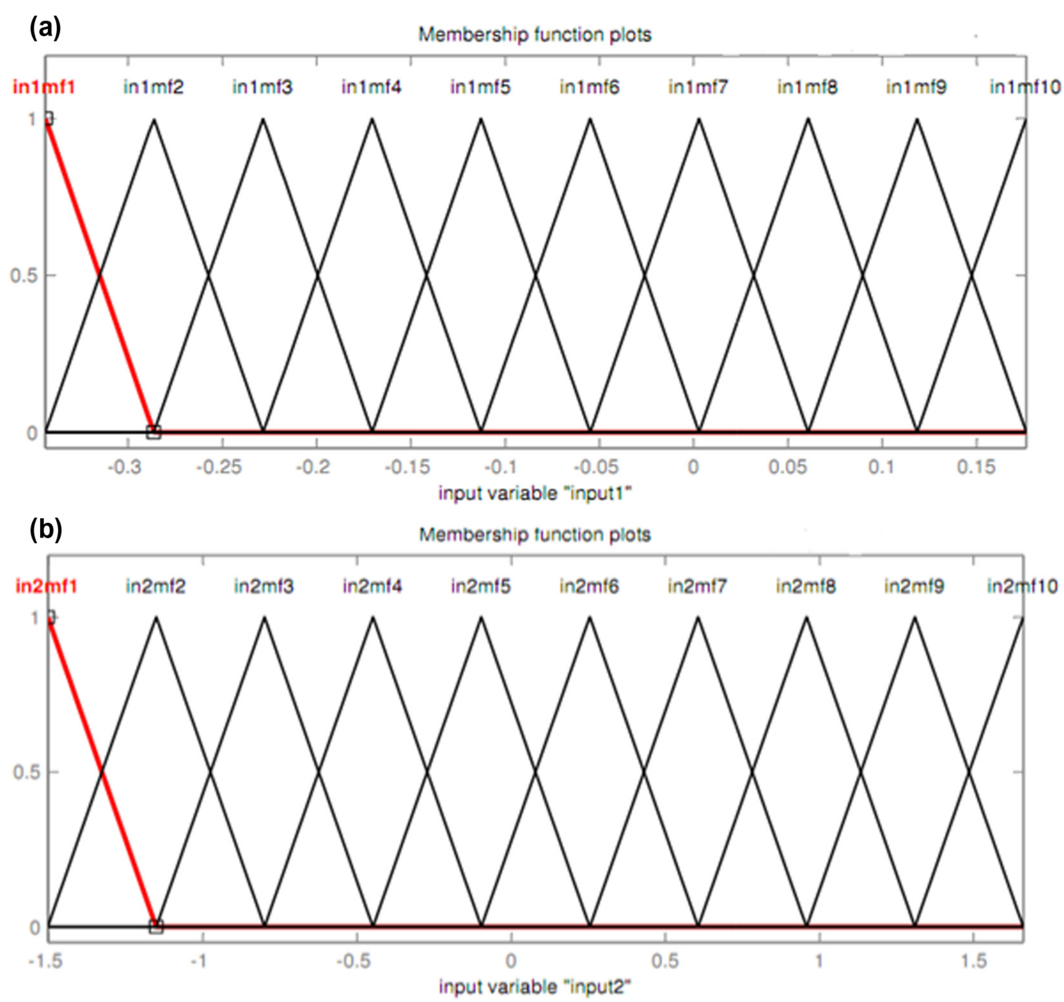

Fig. 4. Membership functions and value gaps of CF1 and CFac of the input variables of ANFIS. (a) Input membership functions, CF1 and (b) input membership functions, CFac.

3.1.1. CPS1

The CPS1 standards are the modified version of A1 criterion. Before 1997 control performance parameters considered different criteria like A1, A2, B1 and B2. A1 criterion requires that Area Control Error (*ACE*) return to zero within ten minutes of previously reaching zero. A2 criterion requires that the average *ACE* for each of the six ten-minute periods during the clock hour is within specific limits referred as L_{10}. Instead of requiring ACE to cross zero at least once every ten minutes, CPS1 takes a more reasonable approach based upon statistical theory [20].

An expression, which represent the control area's contribution to the reliability of an interconnected power system quantitatively is called the Compliance Factor (*CF*), which having two components, frequency deviation (ΔF) and *ACE*. Whenever, a control area has a non-zero ACE and there is a ΔF at the same time, a non-zero CF is formed that could be either positive or negative depending upon the signs of *ACE* and ΔF at the moment. A positive *CF* denotes that the control area is acting as a burden to the interconnections regulation requirement for that particular time and in the case of negative *CF* it will help the regulation requirement of the interconnection [18–20,26].

To calculate *CPS1*, clock minute average information of *ACE* and ΔF are used for latest 12 months. $(ACE)_{1\ \text{minute}}/((\Delta F)_{1\ \text{minute}}$ is defined by the algebraic sum of $ACE/\Delta F$ samples divided by the number of samples. For example, for a system that samples *ACE* every 4 s the average of *ACE* over a 1 min period would be defined by the algebraic sum of 15 *ACE* samples divided by 15.

One minute compliance factor of the *i*th area is given by

$$CF_1 = \left[\left(\frac{ACE}{-10B}\right)_1 \left(\frac{\Delta F}{\varepsilon_1^2}\right)_1\right] \tag{11}$$

where *B* is the frequency bias constant of the *i*th control area and ε_1 targeted frequency bound for CPS1.

Accumulated compliance factor is given by

$$CF_{ac} = AVG_{12\ month}[(CF1)] \tag{12}$$

$$CPS1\ in\ \% = (2 - CF_{ac}) * 100 \tag{13}$$

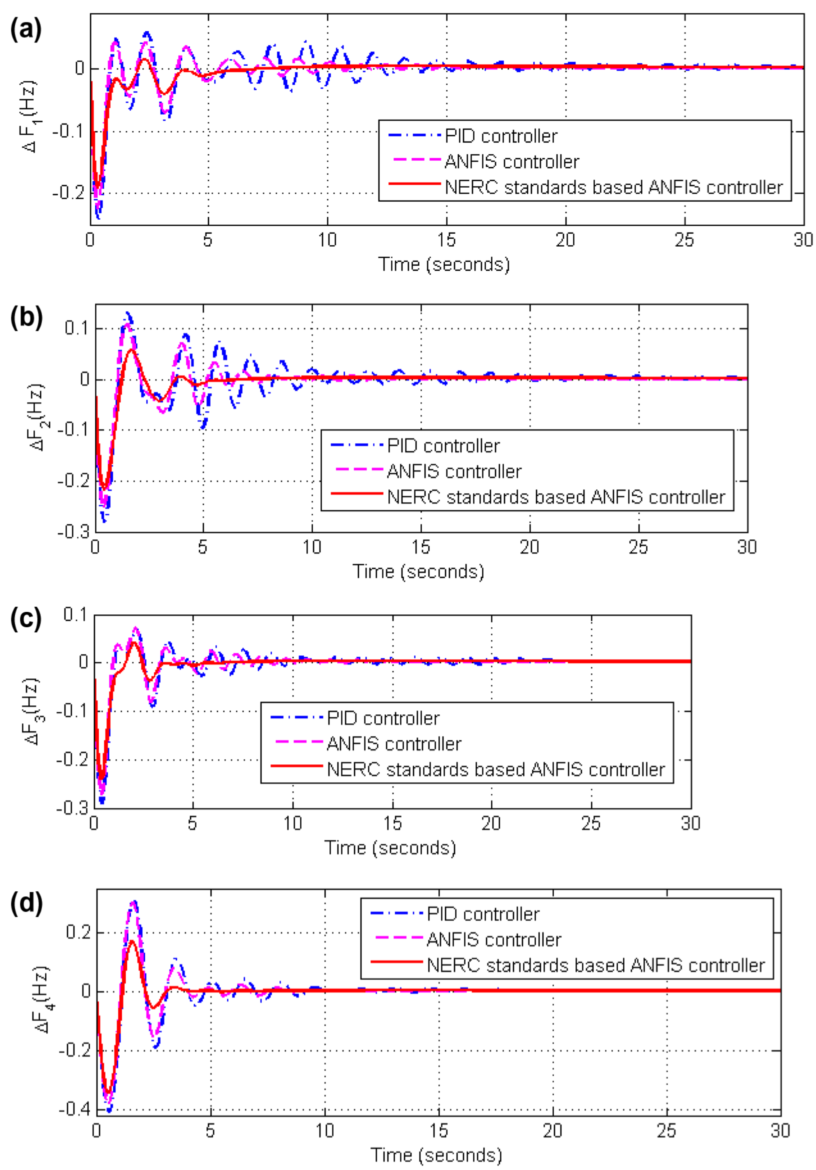

Fig. 5. Dynamic response of the test system under unilateral contract scenario. (a) Frequency deviations in area-1. (b) Frequency deviations in area-2. (c) Frequency deviations in area-3. (d) Frequency deviations in area-4.

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A control area must calculate its CPS1 by each minute. To comply with NERC standards CPS1 should not be less than 100%.

3.1.2. CPS2

CPS2 is very similar to that of A2 criterion. It takes over a clock ten minute period, the ten minute averages of a control area's *ACE* is taken as $AVG\,(ACE)_{10\ \mathrm{minute}}$ less than the constant L_{10}. $AVG\,(ACE)_{10\ \mathrm{minute}}$ is defined by the algebraic sum of *ACE* samples divided by the number of samples [24]. According to BAL-001-2, CPS2 having

(i) Doesn't have a frequency component.
(ii) Requires Balancing Authorities to comply 90 percent of the time as a minimum. The detailed description of CPS2 is described below.

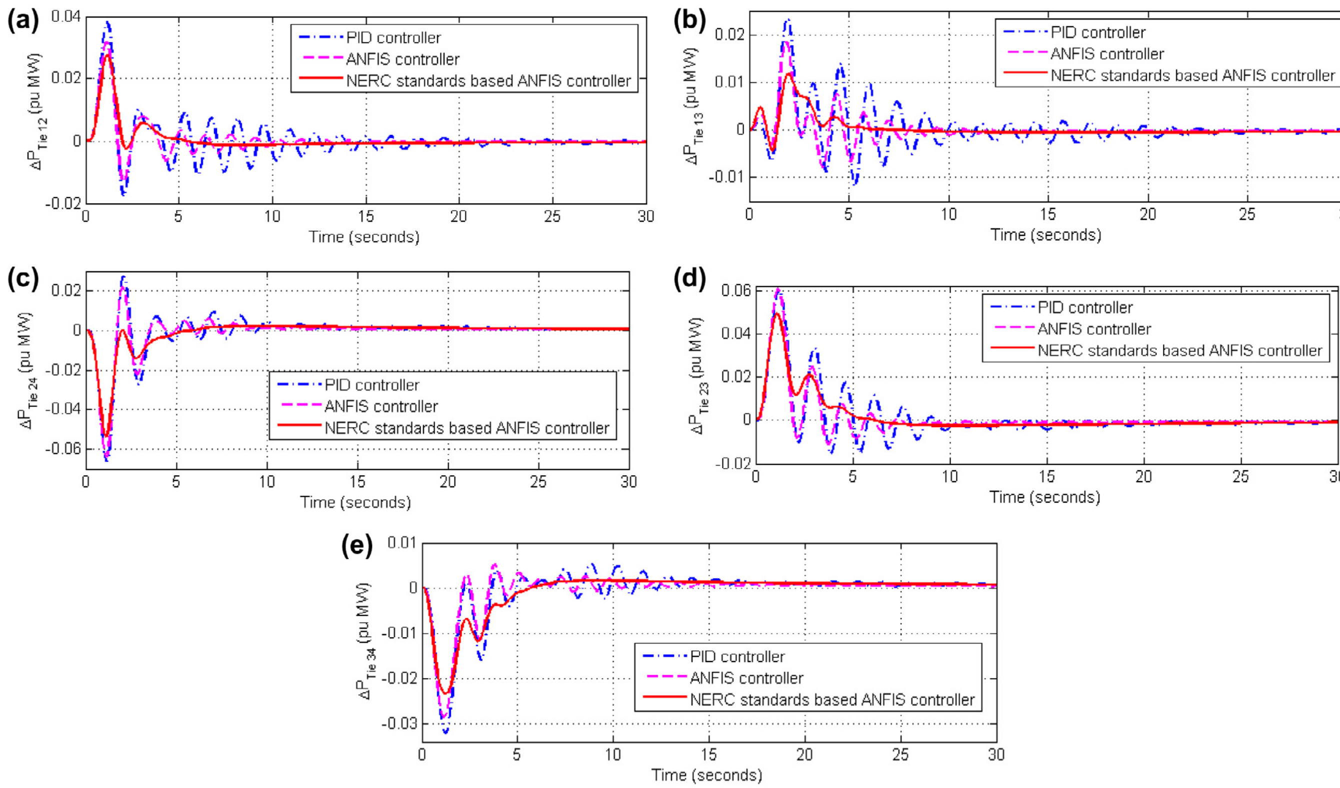

Fig. 6. Dynamic response of the test system under unilateral contract scenario. (a) Tie-line power deviations between area-1&2. (b) Tie-line power deviations between area-1&3. (c) Tie-line power deviations between area-2&4. (d) Tie-line power deviations between area-2&3. (e) Tie-line power deviations between area-3&4.

Table 1
Time domain analysis of various controllers under different contract cases.

System responses		Controllers								
		PID Controller			ANFIS Controller			NERC standards based ANFIS Controller		
		Case 1	Case 2	Case 3	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
ΔF_1	OS	0.0654	0.0763	0.1382	0.0518	0.0532	0.0038	0.0193	0.0141	0.0009
	US	−0.285	−0.232	−0.379	−0.240	−0.210	−0.210	−0.187	−0.179	−0.178
	Ts	20	22	24	11	13	11	6	6	6
ΔF_2	OS	0.136	0.2000	0.2000	0.1005	0.1842	0.1862	0.0561	0.1498	0.052
	US	−0.285	−0.368	−0.352	−0.253	−0.302	−0.300	−0.218	−0.254	−0.209
	Ts	19	19	19	9	9	9	5	5	5
ΔF_3	OS	0.0756	0.1023	0.1002	0.0741	0.1000	0.0996	0.0327	0.0455	0.045
	US	−0.287	−0.238	−0.250	−0.276	−0.221	−0.241	−0.230	−0.212	−0.209
	Ts	20	20	20	10	9	9	4	6	6
ΔF_4	OS	0.286	0.269	0.302	0.2745	0.270	0.300	0.175	0.171	0.175
	US	−0.412	−0.410	−0.586	−0.388	−0.380	−0.400	−0.355	−0.350	−0.380
	Ts	12	12	12	10	10	9	5	5	5
ΔP_{Tie12}	OS	0.0387	0.0653	0.0682	0.0321	0.0572	0.0576	0.0276	0.0486	0.0482
	US	−0.0189	−0.0185	−0.031	−0.0132	−0.008	−0.011	−0.0025	−0.000	−0.001
	Ts	22	23	24	12	11	11	6	6	6
ΔP_{Tie34}	OS	0.0062	0.0102	0.0223	0.0042	0.0094	0.0934	0.0021	0.001	0.0022
	US	−0.031	−0.0258	−0.030	−0.0289	−0.0224	−0.021	−0.022	−0.0175	−0.0183
	Ts	18	23	23	11	14	14	7	7	7
ΔP_{Tie24}	OS	0.0284	0.0251	0.0233	0.020	0.0247	0.0228	0.0015	0.0010	0.0005
	US	−0.065	−0.081	−0.112	−0.062	−0.079	−0.075	−0.050	−0.067	−0.068
	Ts	16	14	16	10	10	10	7	7	7
ΔP_{Tie23}	OS	0.060	0.050	0.061	0.0592	0.046	0.049	0.050	0.0371	0.038
	US	−0.018	−0.020	−0.02	−0.010	−0.01	−0.01	−0.0012	−0.001	−0.001
	Ts	17	17	18	11	11	11	7	7	7

This should be less than the constant L_{10}.

$$AVG_{10-\min}(ACE_i) \leqslant L_{10} \tag{14}$$

$$L_{10} = 1.65\varepsilon_{10}\sqrt{(-10B_i)(-10B_s)} \tag{15}$$

where B_i the frequency bias of ith control area is, B_s is the summation of frequency bias settings of all areas and ε_{10} is the targeted frequency bound of CPS

$$CPS2 = \left[1 - \frac{Violations_{month}}{Totalperiod - unavailableperiod}\right] \times 100\% \tag{16}$$

where $Violations_{month}$ is a count of the number of periods that the clock-10-min average of ACE is greater than L_{10} in one month. To comply with NERC standards CPS2 should not be less than 90%.

3.1.3. BAAL

The balancing authority ACE limits (BAAL) are unique for each balancing authority and provide dynamic limit for its ACE value limit as a function of its interconnected system frequency. BAAL is defined by two equations; $BAAL_{Low}$ and $BAAL_{High}$. When the actual frequency is equal to schedule frequency, $BAAL_{High}$ and $BAAL_{Low}$ do not apply. When actual frequency is less than the scheduled frequency, $BAAL_{High}$ does not apply, and $BAAL_{Low}$ is calculated as [23,24]:

$$BAAL_{Low} = (-10B_i \times (FTL_{Low} - F_S)) \times \frac{(FTL_{Low} - F_s)}{(F_A - F_S)} \tag{17}$$

When actual frequency is less than the scheduled frequency, $BAAL_{Low}$ doesn't apply, and $BAAL_{High}$ is calculated as:

$$BAAL_{High} = (-10B_i \times (FTL_{High} - F_S)) \times \frac{(FTL_{High} - F_s)}{(F_A - F_S)} \tag{18}$$

where

$$\begin{aligned} FTL_{Low} &= F_S - 3\varepsilon 1_1\text{Hz and} \\ FTL_{High} &= F_S + 3\varepsilon 1_1\text{Hz} \end{aligned} \tag{19}$$

where F_A and F_S are the measured frequency in Hz, 10 is a constant to convert the frequency bias setting from MW/0.1 Hz to MW/Hz.

B_i is the frequency bias setting and is expressed in MW/0.1 Hz. $\varepsilon 1_1$ is RMS value of the targeted frequency error for each interconnection and its typical values is taken as 0.018 Hz.

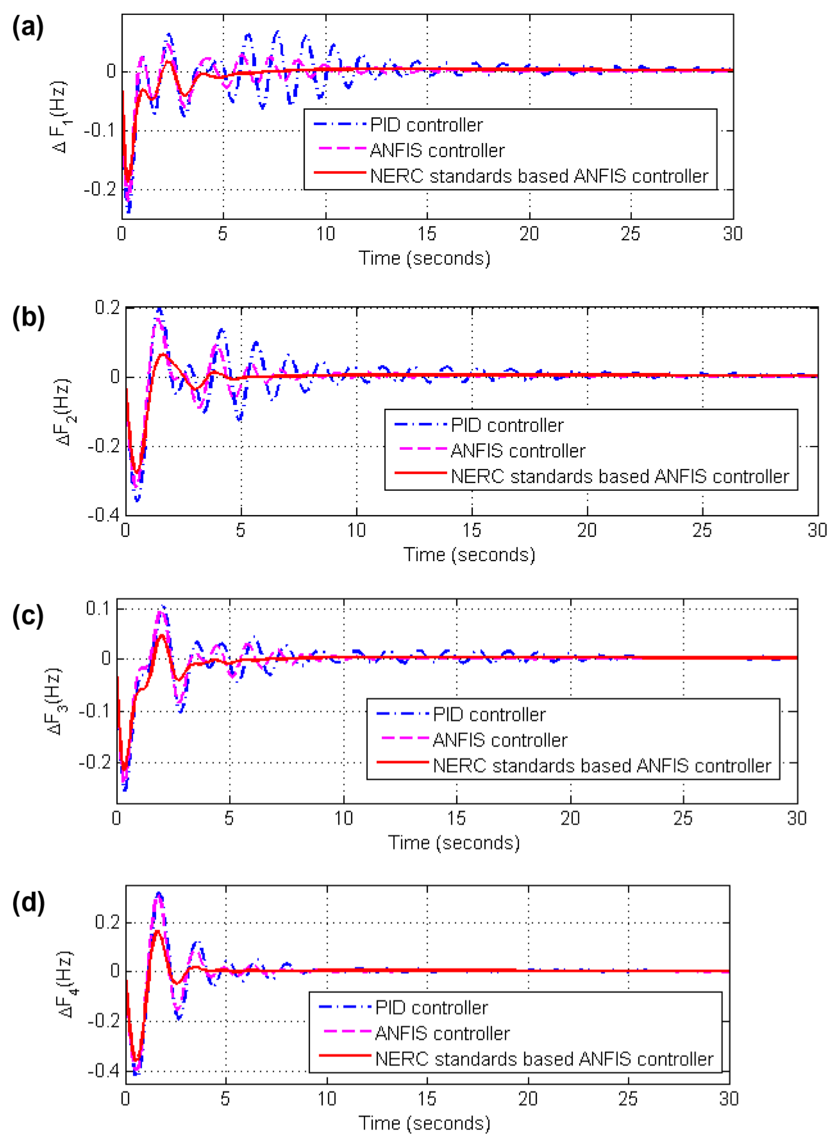

Fig. 7. Frequency deviation of the test system under unilateral contract scenario. (a) Frequency deviations in area-1. (b) Frequency deviations in area-2. (c) Frequency deviations in area-3. (d) Frequency deviations in area-4.

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To comply with NERC standards, each balancing authority exceeded its clock-minute BAAL which should not be less than 30 consecutive clock minutes for $BAAL_{Low}$ and not less than or equal to 45 consecutive clock-minutes for $BAAL_{High}$.

4. Theory of ANFIS controller

ANFIS architecture is a hybrid combination of neuro and fuzzy approaches and it is deemed as an adaptive network having zero synaptic weight. An Adaptive network having no synaptic weight is also called as adaptive and non-adaptive nodes. An adaptive network can easily transform to neural network architecture with classical feed forward topology. The ANFIS controller works like an adaptive network simulator of Takagi–Sugeno type fuzzy controller. ANFIS controller is functionally equivalent to a fuzzy inference system (FIS) and its operations are performed under Takagi–Sugeno type fuzzy controller. According to the input/output data sets, ANFIS adjust the parameters using back propagation gradient descent and least square types of method for non-linear and linear parameters respectively.

From Fig. 2, the two different rule bases for ANFIS structure is explained as [27–29]:

If x is A_1 and y is B_1 then $f_1 = p_1x + q_1y + r_1$
If x is A_2 and y is B_2 then $f_2 = p_2x + q_2y + r_2$

Where p, r, and q are the linear output parameters. ANFIS structure including inputs and outputs which are shown in Fig. 3. For the creation of this architecture we used five layers and two *if–then* rules:

Layer-1: Every node i in this layer is a square node with a node function.

$$o_i^1 = \mu_{Ai}(x), \quad \text{for } i = 1,2 \text{ and}$$
$$o_i^1 = \mu_{Bi-2}(y), \quad \text{for } i = 3,4 \tag{20}$$

where x and y are denoted as the input to node I and Ai and Bi are taken as linguistic labels for inputs. Or $o_{i,1}$ is the member function of Ai and Bi. In general,

$$\mu_{Ai}(x), \mu_{Bi-2}(y) = \frac{1}{1 + ((x - c_i)/\alpha_i)^2} \tag{21}$$

$$\mu_{Ai}(x), \mu_{Bi-2}(y) = \exp\left[-((x - c_i)/\alpha_i)^2\right] \tag{22}$$

where α_i, c_i are taken as the parameter set. These parameters in this layer are referred to as premise parameters.

Layer-2: Every node in this layer is a circle node labeled Π which multiplies the incoming signals and sends the product out. For instance,

$$o_i^2 = \mu_{Ai}(x), \mu_{Bi-2}(y), \quad i = 1,2 \tag{23}$$

Each node output represents the firing strength of a rule.

Layer-3: Every node in this layer is a circle node labeled N. The ith node calculates the ratio of the ith rule's firing strength to the sum of all rule's firing strengths:

$$o_i^3 = \overline{w}_i = \frac{w_i}{w_1 + w_2} \tag{24}$$

Layer-4: Every node i in this layer is a square node with a node function

$$o_i^4 = \overline{w}_i \cdot f_i = w_i \cdot (p_ix + q_iy + r_i), \quad i = 1,2 \tag{25}$$

where w_i is the output of layer 3 and $\{p_i, q_i, r_i\}$ is the parameter set. Parameters in this layer will be referred as consequent parameters.

Layer-5: The single node in this layer is a circle node labeled $\sum$ that computes the overall output as the summation of all incoming signals:

$$o_i^5 = \text{overall output} = \sum_i \overline{w}_i \cdot f_i = \frac{\sum_i w_i f_i}{\sum_i w_i} \tag{26}$$

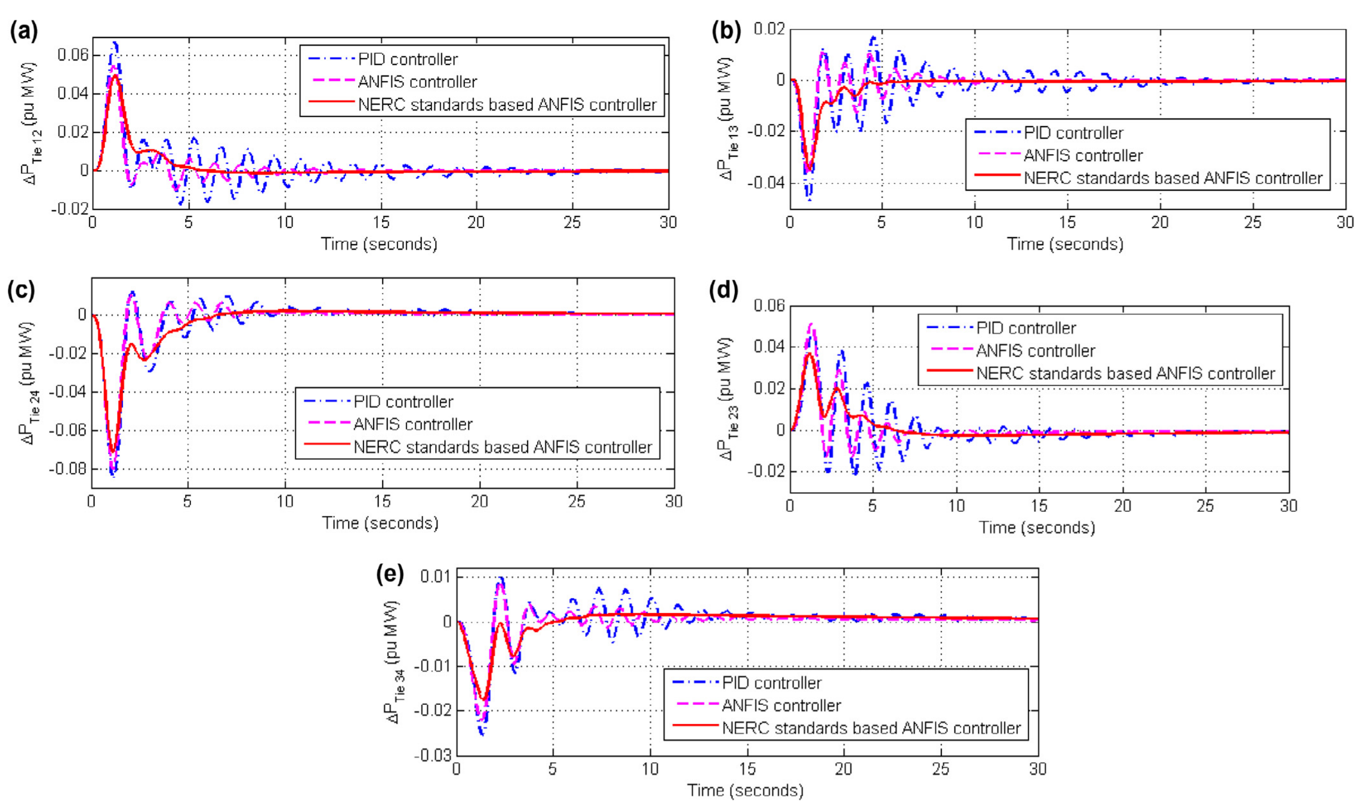

Fig. 8. Dynamic response of the test system under bilateral contract scenario. (a) Tie-line power deviations between area-1&2. (b) Tie-line power deviations between area-1&3. (c) Tie-line power deviations between area-2&4. (d) Tie-line power deviations between area-2&3. (e) Tie-line power deviations between area-3&4.

In this article, the ANFIS controller uses the back propagation through time algorithm, which is an advanced adaptive control configuration of ANN. The back-propagation technique is an iterative method employing the gradient decent algorithm for minimizing the minimum square error between the actual output and the objective for each pattern in the training. The ANFIS system consists of the components of a conventional fuzzy system except that computation at every phase is carried out by a layer of hidden neurons and the neural network's learning capacity is offered to boost the system knowledge [27–30].

5. Design of NERC standards based ANFIS controller

The proposed "NERC standard based ANFIS controller" is designed for the following objectives. They are

(i) To design a suitable control for mitigating the different LFC problems in a deregulated power system.
(ii) To compare the proposed controller results with NERC standards CPS1 CPS2 and BAAL values.
(iii) To reduce the wear and tear of the generating unit's equipment.

The proposed ANFIS controller utilizes Sugeno-type fuzzy inference system (FIS) controller. The FIS parameters are decided by the neural-network back propagation method. If input–output data is observed for the system, the components of a fuzzy system (membership and consequent models) can be represented in a parametric form and the parameters can be tuned by neural networks. So the entire framework will be considered as neuro-fuzzy system [27].

ANFIS rule based load frequency control for NERC standard based controller is shown in Fig. 3. In the design of NERC standards based ANFIS controller, the input signals to the ANFIS controller are one minute compliance factor CF1 and accumulated compliance factor CFac which are explained in Eqs. (11) and (12) respectively

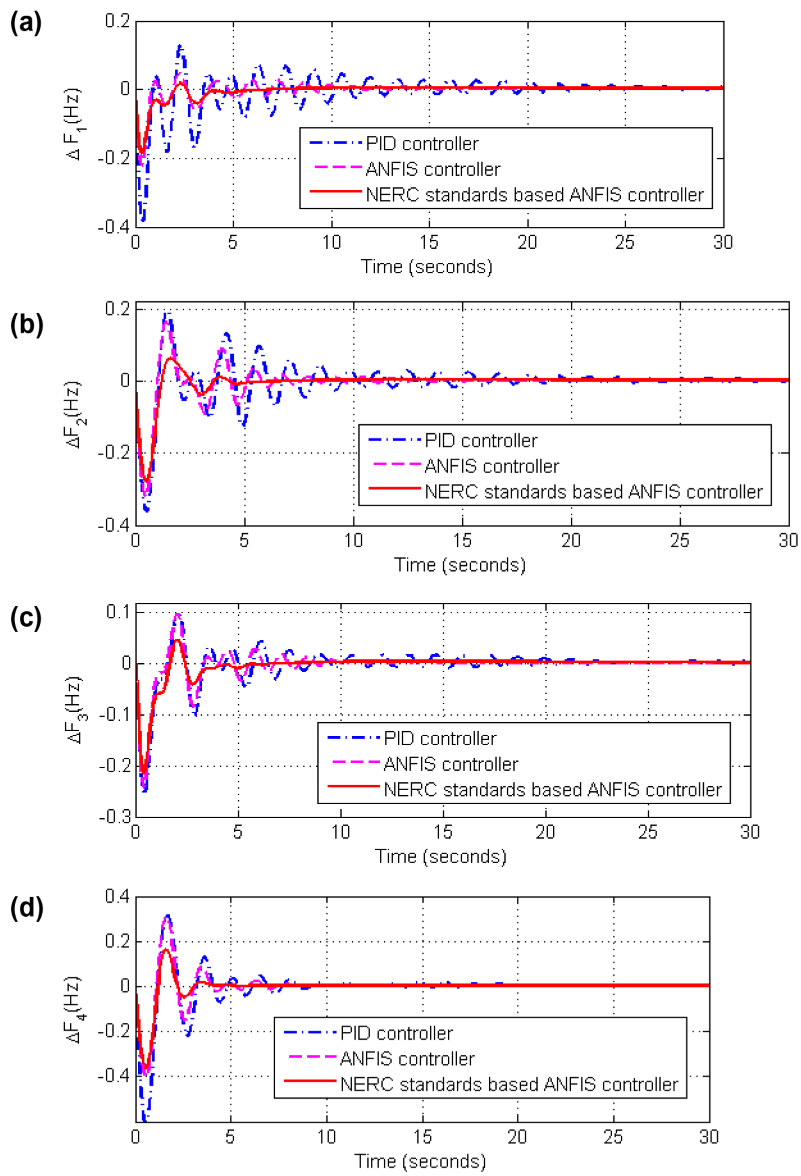

Fig. 9. Dynamic response of the test system under contract violation scenario. (a) Frequency deviations in area-1. (b) Frequency deviations in area-2. (c) Frequency deviations in area-3. (d) Frequency deviations in area-4.

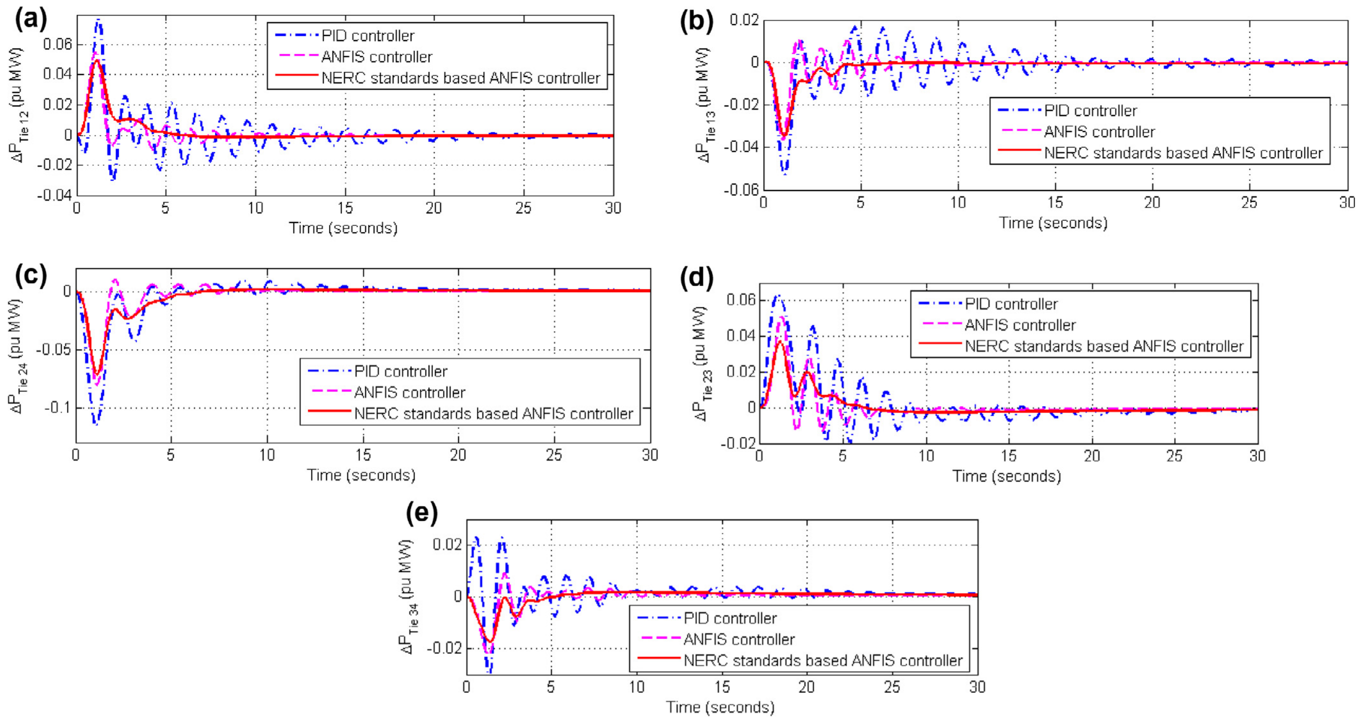

Fig. 10. Dynamic response of the test system under contract violation scenario. (a) Tie-line power deviations between area-1&2. (b) Tie-line power deviations between area-1&3. (c) Tie-line power deviations between area-2&4. (d) Tie-line power deviations between area-2&3. (e) Tie-line power deviations between area-3&4.

and the output is the neuro-fuzzy gain α. The triangle type membership functions of input signals CF1 and CFac of this fuzzy interface system are shown in Fig. 4. The output gain is used to tune the control parameter of the PID controller. ANFIS-Editor is used for realizing the system and its implementation. The fuzzy controller uses 100 rules and 10 membership functions in each variable to compute the output and it exhibits good performance. The rule base of ANFIS are created by using a logical operator between the input and output signals of system with (if, then) words. The input variables of ANFIS are combined with "and" conjunction. It is obtained through *anfisedit* software of Matlab/Simulink program and implemented in the proposed system.

The basic steps for the ANFIS controller design in MATLAB/Simulink environment (Fig. 1) are mentioned below [6,27]

(1) Model and simulate the test system with simulink and fuzzy logic controller with the given rule base.
(2) Collect the training data while simulating the model with fuzzy logic controller.
(3) The two inputs, i.e., CF1 and CFac and the output signal provides the training data.
(4) Use *anfisedit* to generate the ANFIS *.fis* file.
(5) Arrange the training data collected in Step 2 and generate the FIS with Gaussian membership function.
(6) Trains the collected data with the generated FIS up to a particular no. of Epochs.
(7) Save the FIS. This FIS file is the Neuro-Fuzzy enhanced ANFIS file.

6. Simulation results and discussions

The proposed NERC standards based ANFIS controller is implemented in the four area deregulated power system as shown in Fig. 1. This power system model consists of three thermal GENCOs, one hydro GENCO and four DISCOs. The numerical parameters of

Table 2
Percentage values of CPS1 values of three different controllers.

Recoded Time	Real time data from Indian grid	Controllers		
		PID controller	ANFIS controller	NERC standards based ANFIS controller
Percentage value of CPS1				
18:30–18:40	85	117	137	103
18:40–18:50	90	120	140	104
18:50–19:00	94	123	142	106
19:00–19:10	90	119	138	103
19:10–19:20	89	118	136	102
19:20–19:30	89	117	138	103
19:30–19:40	92	121	141	106
19:40–19:50	85	115	135	101
19:50–20:00	90	120	139	103
20:00–20:10	91	120	138	102

Table 3
Percentage values of CPS2 values of three different controllers.

Recoded Time	Real time data from Indian grid	Controllers		
		PID controller	ANFIS controller	NERC standards based ANFIS controller
Percentage value of CPS2				
18:30–18:40	78	97	100	90
18:40–18:50	79	98	101	91
18:50–19:00	81	97	103	92
19:00–19:10	80	95	101	91
19:10–19:20	88	96	105	94
19:20–19:30	82	95	104	92
19:30–19:40	87	98	107	94
19:40–19:50	82	97	102	93
19:50–20:00	79	97	103	92
20:00–20:10	80	98	104	92

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the four area system are taken from Indian regional grid website [25] and are given in Appendix A. Typical load variation data is taken from the Indian Regional Load Dispatched Center website on 22nd June 2016 from 18:30:00 to 20:10:00 h. To check the effectiveness of the proposed controller, simulation studies of the test system are broadly classified into two sections,

Table 4
Consecutive clock minutes of $BAAL_{Low}$ and $BAAL_{High}$ values for three different controllers.

Recoded Time	Real time data from Indian grid		Controllers					
			PID controller		ANFIS controller		NERC standards ANFIS controller	
	$BAAL_{Low}$	$BAAL_{High}$	$BAAL_{Low}$	$BAAL_{High}$	$BAAL_{Low}$	$BAAL_{High}$	$BAAL_{Low}$	$BAAL_{High}$
18:30–18:40	22	29	39	49	43	58	30	47
18:40–18:50	24	30	38	50	42	56	31	46
18:50–19:00	23	28	41	49	42	57	30	47
19:00–19:10	23	28	40	51	43	59	31	45
19:10–19:20	25	26	38	53	44	60	32	45
19:20–19:30	23	26	40	50	42	59	30	46
19:30–19:40	22	26	39	50	44	60	30	45
19:40–19:50	23	26	39	50	42	60	31	45
19:50–20:00	23	26	39	49	43	58	32	46
20:00–20:10	23	26	40	52	42	59	30	45

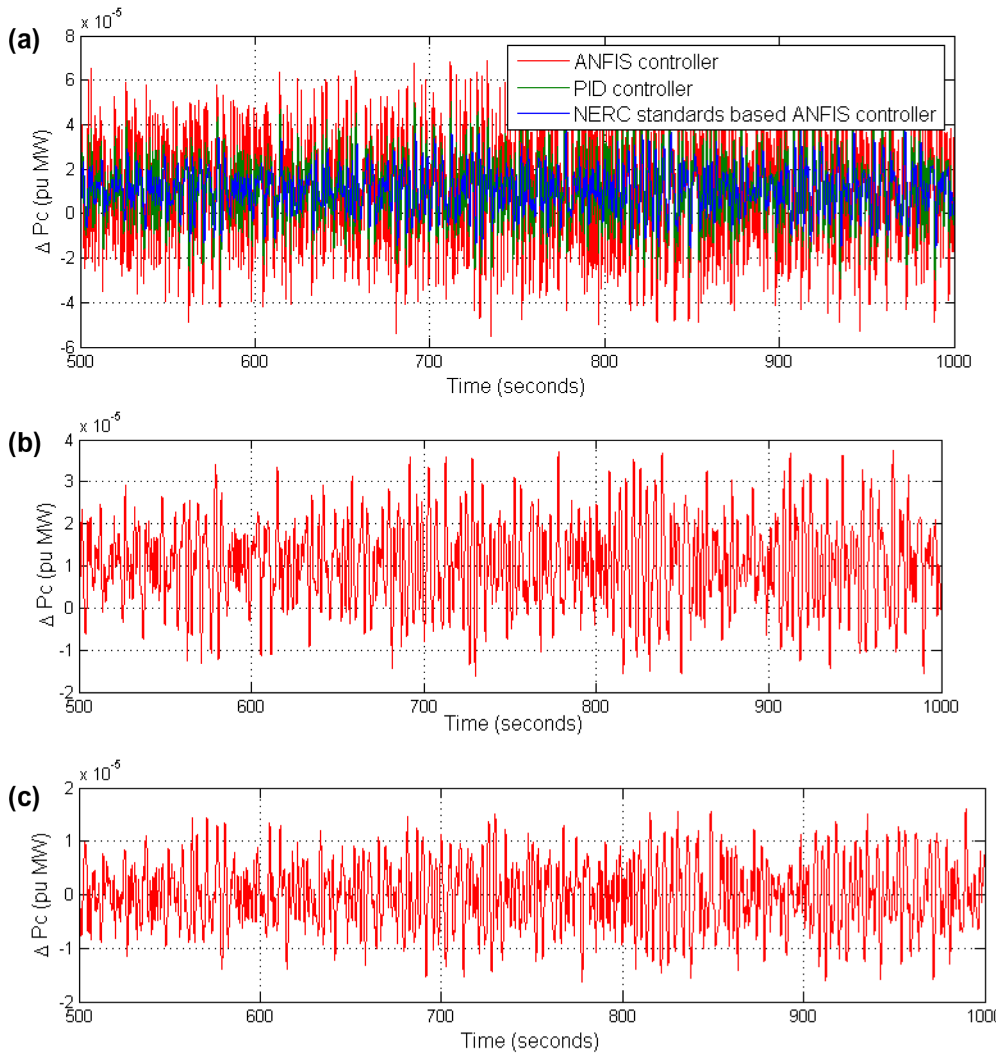

Fig. 11. Excess raise/lower signals of GENCO-1 with three different controllers. (a) Speed changer raise/lower signals of GENCO-1 with three different controllers. (b) Excess raise/lower signals of GENCO-1 of PID controller over NERC standards-based ANFIS controller. (c) Excess raise/lower signals of GENCO-1 of ANFIS controller over NERC standards-based ANFIS controller.

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(i). Time domain analysis of proposed controller with PID and ANFIS controller.
(ii). Performance evaluation of proposed controller with Industrial/academic standards (NERC standards CPS1, CPS2 and BAAL).

6.1. Time domain analysis of NERC standard based ANFIS controller with other controllers

The time domain analysis of the proposed controller in a four area deregulated power system under MATLAB/Simulink environment is shown in Fig. 1. The secondary regulation for this four area system is tested with PID controller, ANFIS controller and the proposed NERC standards based ANFIS controller is discussed below. Time domain simulation results proves that the proposed controller gives good dynamic performance over the other controllers in terms of area frequency oscillations and tie-line power deviations under three different contract cases. The different contract cases are:

- Case1: Unilateral contract.
- Case2: Bilateral contract.
- Case3: Contract violation.

Case 1: Unilateral contract

In this case, DISCOs have the right to contract with GENCOs in the same area only. Load disturbance has occurred in each control area and it is assumed as $\Delta P_{L1} = \Delta P_{L2} = \Delta P_{L3} = \Delta P_{L4}$ =0.1pu. In unilateral case, the contract between DISCOs and available GENCOs are simulated using the following DPM:

$$DPM = \begin{bmatrix} 1.0 & 0 & 0 & 0 \\ 0 & 1.0 & 0 & 0 \\ 0 & 0 & 1.0 & 0 \\ 0 & 0 & 0 & 1.0 \end{bmatrix}$$

The power output ($\Delta P_{GENCO-i}$) of each GENCO can be calculated using Eq. (9) as $\Delta P_{GENCO-1} = 0.1$ pu MW, $\Delta P_{GENCO-2}$ = 0.1 pu MW, $\Delta P_{GENCO-3}$ = 0.1 pu MW, $\Delta P_{GENCO-4}$ = 0.1 pu MW. Frequency deviations and tie-line power oscillations in unilateral contract with different controllers are shown in Figs. 5 and 6 and its values are

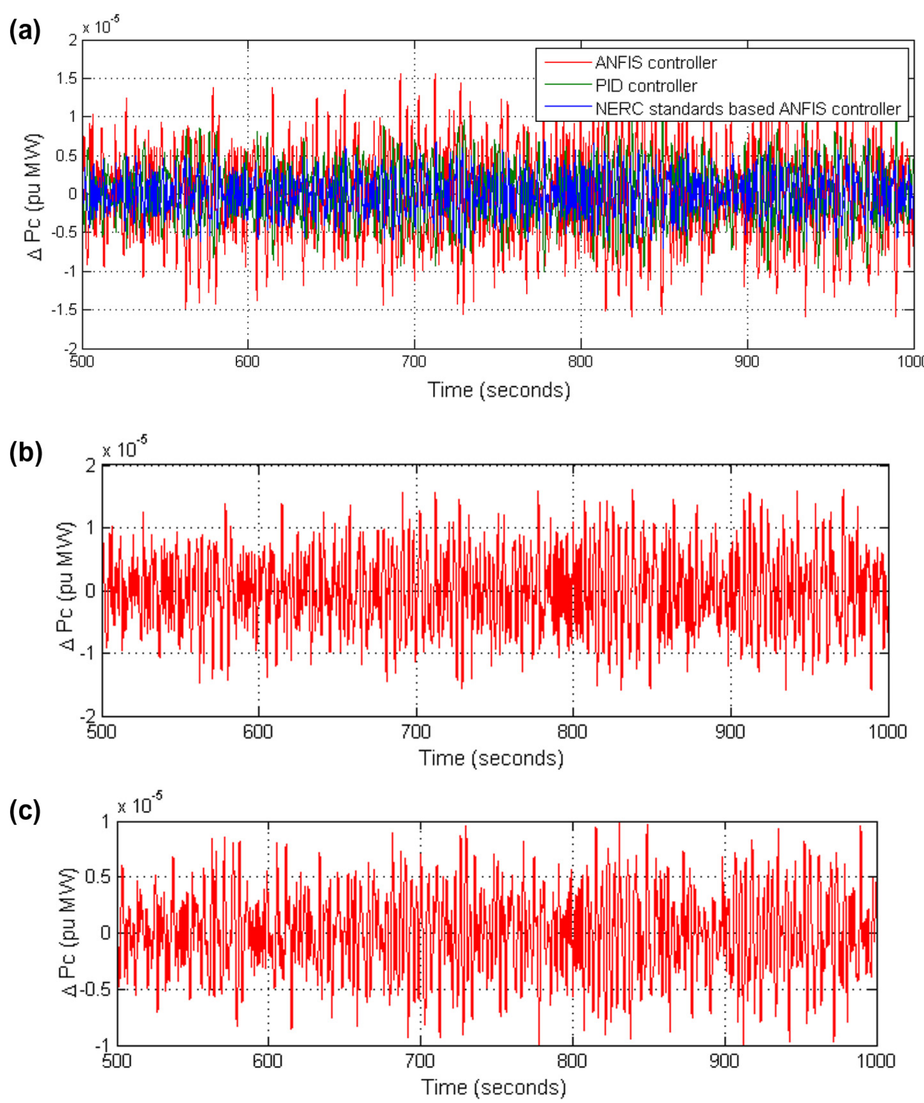

Fig. 12. Excess raise/lower signals of Genco-2 with three different controllers. (a) Speed changer raise/lower signals of GENCO-2 with three different controllers. (b) Excess raise/lower signals of GENCO-2 of PID controller over NERC standards-based ANFIS controller. (c) Excess raise/lower signals of GENCO-2 of ANFIS controller over NERC standards-based ANFIS controller.

depicted in Table 1. It should be clear that frequency and tie-line responses are greatly reduced by the proposed NERC standard based ANFIS controller than other two controllers.

Case 2: Bilateral contract

In this case, DISCOs have the freedom to contract with any number of GENCOs within its control area or other areas. The load demand on each DISCO for bilateral contract is taken as $\Delta P_{L1} = \Delta P_{L2} = \Delta P_{L3} = \Delta P_{L4} = 0.1$ pu. Corresponding DPM is given below

$$DPM = \begin{bmatrix} 0.35 & 0.1 & 0.1 & 0 \\ 0.35 & 0.4 & 0.4 & 0.35 \\ 0.30 & 0.2 & 0.1 & 0.35 \\ 0 & 0.3 & 0.4 & 0.3 \end{bmatrix}$$

Under steady state, GENCOs power outputs are calculated by using Eq. (9) is: $\Delta P_{GENCO-1} = 0.055$ pu MW, $\Delta P_{GENCO-2} = 0.15$ pu MW, $\Delta P_{GENCO-3} = 0.095$ pu MW and $\Delta P_{GENCO-4} = 0.1$ pu MW. Frequency deviations and tie-line power oscillations with regard to peak overshoot, peak under shoot and settling time are shown in Figs. 7 and 8 and its values are given in Table 1. These results illustrate that NERC standard based ANFIS controller provides superior dynamic performance results than other conventional controllers.

Case 3: Contract violation

In this case, DISCOs in an area may violate the contract and demand excess power than specified in the actual contract. This surplus power is not contracted out to any GENCO and it is normally supplied by the GENCOs in the same area as that of the DISCO. This excessive power demand will be replicated as a local

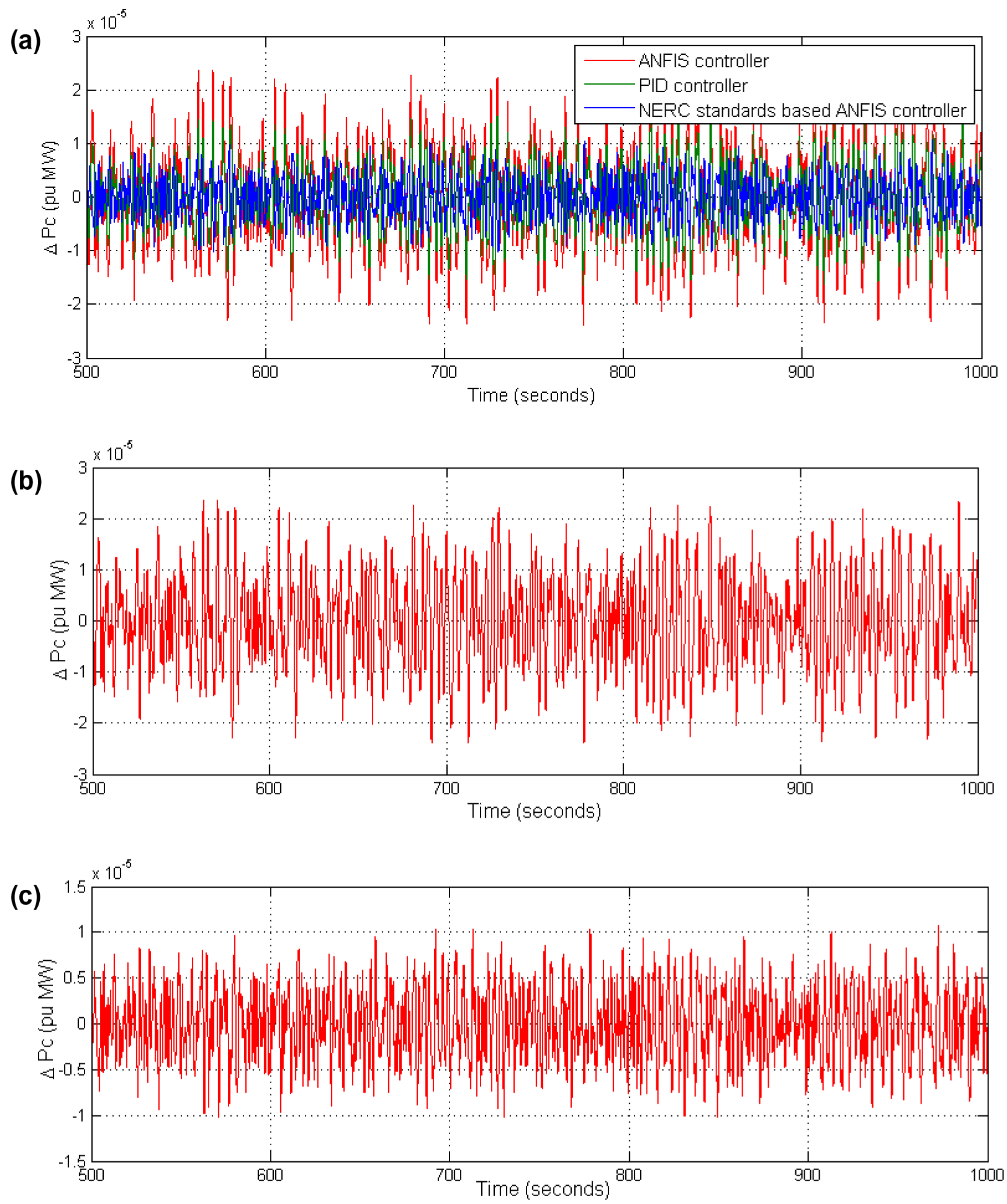

Fig. 13. Excess raise/lower signals of GENCO-3 with three different controllers. (a) Speed changer raise/lower signals of GENCO-3 with three different controllers. (b) Excess raise/lower signals of GENCO-3 of PID controller over NERC standards-based ANFIS controller. (c) Excess raise/lower signals of GENCO-3 of ANFIS controller over NERC standards-based ANFIS controller.

load of that area (uncontracted power demand). Consider the situation where $DISCO_1$ and $DISCO_4$ demand a surplus power of 0.1 pu MW. Frequency and tie-line power deviations in all the control areas settle down to zero and are shown in Figs. 9 and 10 and their analyses in terms of peak overshoot, peak under shoot and settling time are given in Table 1.

6.2. Comparison of proposed controller with NERC standards CPS1, CPS2 and BAAL

For smooth and reliable operation of the entire power system network, NERC suggested three control performance standards CPS1, CPS2 and BAAL values must be within specified limits. For analyzing the effectiveness of the proposed controller, simulation result of the proposed controller is compared with the Indian grid system data. In the present work, load variation data is taken from the Indian grid system and it is assumed that the load variations for one year will be similar to that of one hour sample period. The CF values so computed has been used to calculate CPS1 as defined in Eq. (11). In this work, load variation in area-1 is considered and the targeted frequency bound of the four area system are taken as $\varepsilon_1 = 18$ mHz, and $\varepsilon_{10} = 5.7$ mHz [20].

To demonstrate the advantages of the proposed controller, the percentage of compliance with CPS1of area-1 with three different controllers and real time data are shown in Table 2.

From Table 2, it should be clear that only the proposed controller satisfies the CPS1 value within NERC's prescribed limits (must greater than 100%) than other controllers. Percentage value of CPS2 is calculated by using Eq. (14)–(16). CPS2 values of different controllers in area-1 are shown in Table 3.

From Table 3 it should be clear that only the proposed controller satisfies the CPS2 value within its prescribed limits (not less than 90%) than other controllers.

From Tables 2 and 3, the maximum and minimum values of CPS1 and CPS2 in area-1 obtained from NERC standards based

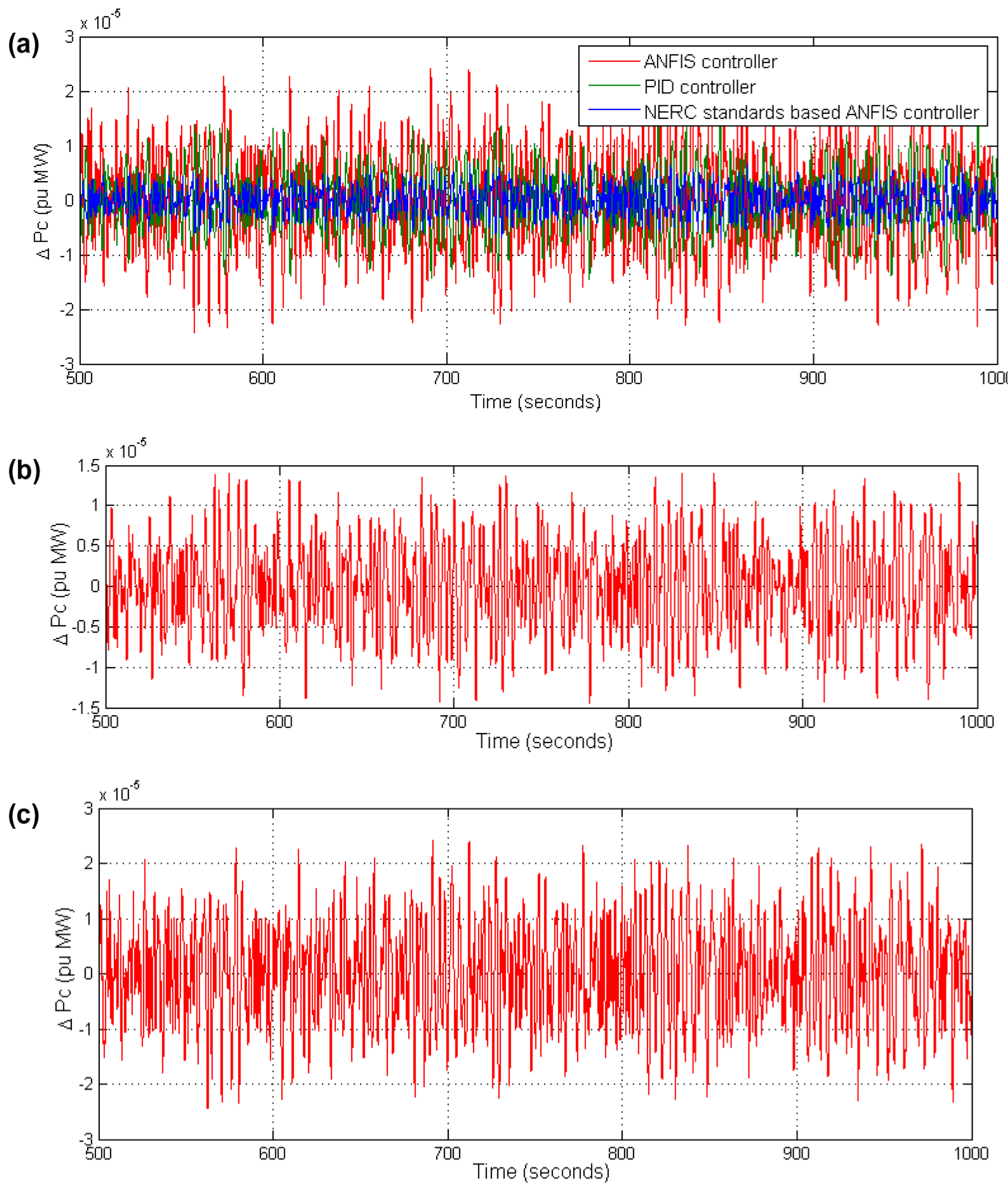

Fig. 14. Excess raise/lower signals of GENCO-4 with three different controllers. (a) Speed changer raise/lower signals of GENCO-4 with three different controllers. (b) Excess raise/lower signals of GENCO-4 of PID controller over NERC standards-based ANFIS controller. (c) Excess raise/lower signals of GENCO-4 of ANFIS controller over NERC standards-based ANFIS controller.

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ANFIS controller results are approximately close to NERC control performance standards. On the other hand, other controller's results are over tuning the turbine and governor parts which leads to unnecessary wear and tear of moving parts.

The BAAL provides each balancing authority a dynamic ACE limit that is a function of interconnection frequency. The $BAAL_{High}$ and $BAAL_{Low}$ equations were developed based on the assumption that the frequency trigger limit (FTL) should be taken as scheduled frequency Fs and the FTL_{Low} and FTL_{High} values are calculated by using Eqns. (17)–(19). The $BAAL_{High}$ and $BAAL_{Low}$ for three different controllers are tabulated in Table 4.

From Table 4 it should be clear that by using NERC standard based ANFIS controller, the $BAAL_{Low}$ and $BAAL_{High}$ values come under the specified limits as per NERC standard. Other conventional controller results are over tuned and it may produce unnecessary wear and tear of the generating parts.

6.3. Reduction of excess maneuvering of generating unit

In order to evaluate the unnecessary wear and tear of the generating parts, speed changer responses (ΔP_c) of each GENCOs in all the control areas with different controllers are examined. Speed changer rise/lower signals (ΔP_c) of GENCO-1 in area-1 for three different controllers are shown in Fig. 11(a). Excess rise/lower signals of PID and ANFIS controller over the NERC standard based ANFIS controller in area-1 are shown in Fig. 11(b) and (c). Similarly, the speed changer variations with three different controllers in GENCO-2, GENCO-3 and GENCO-4 are shown in Figs. 12–14.

It is observed that under NERC standard based ANFIS controller, the speed changer variation will be lesser than the other two controllers. Excess raise/lower signals produced by the conventional PID controller and ANFIS controller create the unnecessary wear and tear of the generating parts. In NERC standard based ANFIS controller, the fuzzy gain signal (α) moderate the control parameters and reduce the excessive tuning of the controller. The excess maneuvering of the PID controller and ANFIS controller signals are plotted to show the superior performance of the NERC standards based ANFIS controller. Hence, to satisfy the NERC control performance standards and also to reduce the wear and tear of the generating unit equipments, the proposed NERC standard based ANFIS controller is suggested for the Indian grid system.

7. Conclusion

This paper proposes a novel control approach for mitigating the LFC issues in a multi area deregulated power system with NERC standards based ANFIS controller. The main objective of the proposed controller is to mitigate the LFC issues and to comply with the NERC control performance standard BAL-001-2. Simulation studies are carried out with the load disturbance value taken from the Indian regional load dispatched center website. Time domain simulation results shows that NERC standards based ANFIS controller gives better improvement in terms of peak overshoot, peak undershoot, settling time than conventional PID and ANFIS controllers. Control performance standards such as CPS1, CPS2 and BAAL values of the proposed controller are incompliance with the NERC standards than other controllers. In the case of control performance standard limits, it is observed that the CPS1, CPS2 and BAAL values obtained from the NERC standard based ANFIS controller gives better compliance with control performance standards (CPS1 and CPS2 values are in between 102–106%, and 90–94% respectively and the $BAAL_{Low}$ and $BAAL_{High}$ values are in between 42–44 and 57–60 respectively). In addition to this, the number of speed changer operations/minute is also very low in the proposed controller and this may lead to reduction of the excessive wear and tear of governor and turbine moving parts.

Appendix A. Numerical parameters for GENCO's in all control area

Data	Area-1 (hydro)	Area-2 (thermal)	Area-3 (thermal)	Area-4 (thermal)
Maximum demand of each area (MW)	2967	11834	7130	10392
Droop characteristic: R (Hz/pu MW)	2.5	2.5	2.5	2.5
Damping constant: D (pu MW/Hz)	0.0019	0.007	0.0043	0.0062
Frequency bias factor: B (s)	0.402	0.407	0.404	0.406
T_P (s)	40	10	17	12
K_P(Hz/pu MW)	204	50	84	57
T_T (s)	–	0.3	0.3	0.3
T_G (s)	–	0.08	0.08	0.08
T_R (s)	5	–	–	–
T_W (s)	1	–	–	–

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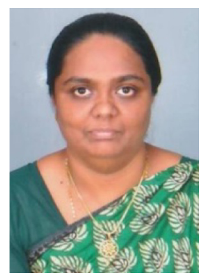
Abhijith Pappachen received his M.Tech degree in Power System from Mahatma Gandhi University, Kottayam, Kerala, India. At present he is working towards the Ph.D. degree at the School of Electrical Engineering, Vellore Institute of Technology, Chennai, India. His research interests are in Deregulated Power System, Power Generation and Operation, Power System Control and Energy Storage Devices.



Dr. A. Peer Fathima has obtained her B.E degree in Electrical & Electronics Engineering from Madurai Kamaraj University, M.E degree in High voltage engineering from Anna University, Chennai, and M.S degree in Electronics & Control from BITS Pilani. She received her Ph.D degree from Anna University, Chennai. She has been in the teaching profession for the past 25 years. She has published over 60 papers in International journals and national conferences. She has guided several P.G and U.G projects. She is guiding seven Ph.D scholars at Anna and VIT universities. Her main teaching and research interest encompasses power system operation and control in deregulated power systems, renewable energy applications in deregulated power systems.