Two-Layered Fuzzy Logic Based Frequency Modulation Controller for a Two-Area Thermal Reheat Power System Interconnected with an AC/DC Hybrid Transmission System

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Abstract: This paper presents new applications of logic technique for designing decentralized controllers for two-area interconnected thermal reheat power systems without and with high voltage direct current [HVDC] parallel link in a AC tie-line. The proposed two layered fuzzy controller, with the updated reference value of area control error [ACE] using pre-compensator ensures the ACE to zero with the inclusion of proportional plus Integral (PI) controllers. The Integral square error technique is adopted in optimizing the PI controller gains. When an AC power system is subjected to load disturbances, considerable frequency oscillations may result to system instability. So as to ensure the system stability, the power modulation control offered by HVDC link is enhanced to suppress the peak value of the transient frequency deviation. Simulation results show that the proposed two layered fuzzy logic controller is not only effective in damping out frequency oscillations, but also capable of alleviating the transient frequency swing caused by large load disturbance. Moreover, the output results prove that the present two layered fuzzy load frequency controller provides very good transient and steady state response compared to the fuzzy controller and conventional PI controller.

Keywords: Load-Frequency Control, Area control error, Integral squared error criterion, Fuzzy logic controller, Flexible AC Transmission system

1. Introduction

Load frequency control (LFC) is a very important issue in power system with an increasing demand for electric power and more complicated. Therefore the objective of LFC of a power system is to maintain the frequency of each area and tie-line power flow (in interconnected system) within specified tolerance by adjusting the new outputs of LFC generators so as to accommodate fluctuating load demand. A number of control schemes have been employed in the design of load frequency controllers [1] in order to achieve better dynamic performance. Among the various types of load frequency controllers the most widely conventional types used are the tie-line bias control and flat frequency control to achieve the above goals of LFC, both schemes are based on the classic controls which work on same function made up of the frequency and tie-line power deviations. Nevertheless these conventional control systems have been successful to some extent only [2]. This suggests the necessity of more advanced control strategies to be incorporated for better control. In this aspect if ensuring a better power quality intelligent controllers [2-8] have been replacing conventional controllers because of their fast and good dynamic response for load frequency control problems.

As the load demand increases tremendously, the power transmission over large distances to the remotely located load centres are forces to emerge into new plant for more and more effective and efficient control schemes for a better secured, reliable and stable system operation. This can be achieved by properly designed load-frequency control schemes i.e either by the proper selection of the controller or by incorporating efficient FACTS devices. [9-12]

In this paper the dynamic performance of two-area thermal reheat power system interconnected with AC tie-line and AC/DC hybrid tie-lines are considered and the PI controllers with various control schemes are designed and verified. In the AC/DC hybrid transmission system the HVDC link quickly starts the control system to suppress the peak value of transient frequency deviation hence a HVDC links is installed in parallel with an AC tie line in order to supply more to the area in need. In practical cases, the system parameters do not remain constant and continuously vary with changing operations.

Fuzzy logic controllers have received considerable interest in recent years. Fuzzy based methods are found to be very useful in the places where the solution to the mathematical formulations is complicated. Moreover, fuzzy logic controller often yields superior results to conventional control approaches [2-5]. The fuzzy logic based intelligent controllers are designed to facilitate the operation smooth and less oscillatory when system is subjected to load disturbances.

In this paper, the control scheme consists of two layers viz fuzzy pre-compensator and fuzzy PI controller. The purpose of the fuzzy pre-compensator is to modify the command signals to compensate for the overshoots and improve the steady state error. Fuzzy rules from the overall fuzzy rule vectors are used at the first layer, linear combination of independent fuzzy rules are used at the second layer. The two layer fuzzy system has less number of fuzzy rules as compared with the fuzzy logic system. The proposed two layered fuzzy logic controllers give better simulation results which is compared with the simulation results obtained using the fuzzy logic controllers and conventional controllers. Thus the two layered fuzzy PI controller enhances an efficient way of coping with imperfect information, offers flexibility in decision making processes

2. Application of AC/DC Hybrid Transmission System for the Proposed Work

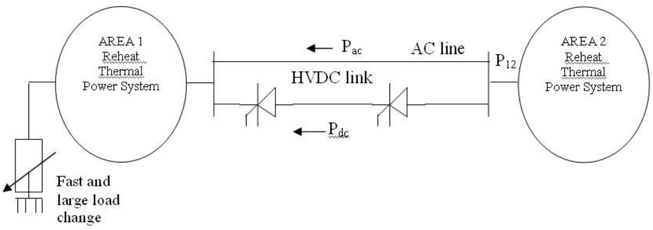


Figure 1. Two-area thermal reheat power system interconnected with an AC/DC hybrid transmission system

In the AC/DC hybrid transmission system the HVDC link consists mainly of a rectifier at the area 2 side, an inverter at the area 1 side and a DC transmission line apart from AC transmission line. In this system, It is assumed that, area 2 has supplied power P_{Ac} via only AC line to area 1. Next, there are installations of large loads with sudden charge in area 1. Therefore, the demand of electric power in area 1 increases further more and these large load change causes a serious problem of frequency oscillations in area 1. This implies that the capabilities of frequency control of governors in area 1 are not capable of stabilizing the frequency oscillations. On the other hand area 2 has enough frequency control capability to compensate for area 1. Therefore area 2 has an HVDC link installed in parallel with an AC tie-line in order to supply more power to area 1[13, 14].

In addition, area 2 offers stabilization of frequency oscillations to area 1 via HVDC link. The DC tie-line power modulation is capable of stabilizing frequency oscillations of area1 by complimentarily utilizing the control capability of area 2. According to the proposed control, the power system that has large capability of frequency control is able to offer service of frequency stabilization for other interconnected areas so that they do not have insufficient capabilities. The proposed control strategy can also be expected as a new ancillary service for stabilizing frequency oscillations.

The frequency modulation controller is modeled as a proportional controller of active power. It should be noted that the power modulation output of HVDC link [ΔP_{dc}], acting positively on area, reacts negatively an another area in an interconnected system ΔP_{dc},, therefore flow into both areas with different sign[+, -] simultaneously the time constant T_{dc} of proportional controller is set appropriately at 0.5[sec] in the simulation study.

3. Problem formulation

3.1 Model 1:

The linearized mathematical model of two – area thermal reheat power system is shown in figure 2 is represented by state variable equation as follows

The state space equations are

$$\dot{x} = Ax + Bu + \Gamma d \qquad (1)$$

$$y = Cx \qquad (2)$$

where $x = [x_1^T, \Delta p_{ei} \ldots x_{(N-1)}^T, \Delta p_{e(N-1)} \ldots x_N^T]^T$, n - state vector

$$n = \sum_{i=1}^{N} n_i + (N-1)$$

$$u = [u_1, \ldots u_N]^T = [\Delta P_{C1} \ldots P_{CN}]^T, N \text{ -}$$

Control input vector

$$d = [d_1, \ldots d_N]^T = [\Delta P_{D1} \ldots P_{DN}]^T, N \text{ -}$$

Disturbance input vector

$y = [y_1 \ldots y_N]^T$, $2N$ - Measurable output vector

where A is system matrix, B is the input distribution matrix, Γ is the disturbance distribution matrix, C is the control output distribution matrix, x is the state vector, u is the control vector and d is the disturbance vector consisting of load changes.

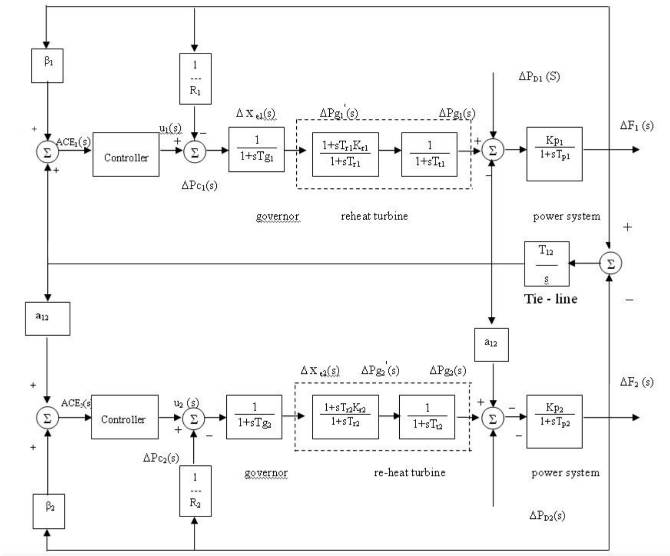


Figure 2. Block diagram of a two – area interconnected power system with reheat turbines

3.2 State Space Model

From the transfer function model shown in Fig.2 the following equation can be written by inspection.

$$\Delta \dot{F}_1 = \frac{k_{p1}}{T_{p1}}\left(\Delta P_{G1} - \Delta P_{D1} - \Delta P_{tie,1}\right) - \frac{\Delta F_1}{T_{p1}} \qquad (3)$$

$$\Delta \dot{P}_{G1} = -\frac{1}{T_{r1}}\Delta P_{G1} + \left[\frac{1}{T_{r1}} - \frac{k_{r1}}{T_{t1}}\right]\Delta P'_{G1} + \frac{k_{r1}}{T_{t1}}\Delta X_{E1} \quad (4)$$

$$\Delta \dot{P}'_{G1} = -\frac{1}{T_{t1}}\Delta X_{E1} - \frac{1}{T_{t1}}\Delta P'_{G1} \quad (5)$$

$$\Delta \dot{X}_{E1} = -\frac{1}{T_{g1}}\Delta X_{E1} + \frac{1}{T_{g1}}\Delta P_{c1} - \frac{1}{T_{g1}R_1}\Delta F_1 \quad (6)$$

$$\Delta \dot{P}_{tie,1} = T_{12}\left(\Delta F_1 - \Delta F_2\right) \quad (7)$$

$$\Delta \dot{F}_2 = \frac{k_{p2}}{T_{p2}}\left(\Delta P_{G2} - \Delta P_{D2} - a_{12}\Delta P_{tie,1}\right) - \frac{\Delta F_2}{T_{p2}} \quad (8)$$

$$\Delta \dot{P}_{G2} = -\frac{1}{T_{r2}}\Delta P_{G2} + \left[\frac{1}{T_{r2}} - \frac{k_{r2}}{T_{t2}}\right]\Delta P'_{G2} + \frac{k_{r2}}{T_{t2}}\Delta X_{E2} \quad (9)$$

$$\Delta \dot{P}'_{G2} = -\frac{1}{T_{t2}}\Delta X_{E2} - \frac{1}{T_{t2}}\Delta P'_{G2} \quad (10)$$

$$\Delta \dot{X}_{E2} = -\frac{1}{T_{g2}}\Delta X_{E2} + \frac{1}{T_{g2}}\Delta P_{c2} - \frac{1}{T_{g2}R_2}\Delta F_2 \quad (11)$$

3.3 Model 2:

The linearized mathematical model of two area thermal reheat interconnected system with HVDC links shown in Figure. 3 and state variable equations as follows

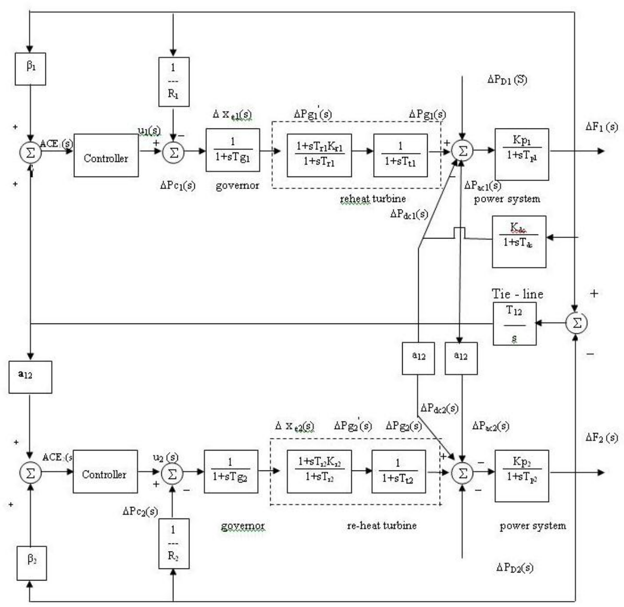


Figure 3. Block diagram of a two – area reheat thermal power system interconnected with AC/DC hybrid transmission system

$$\Delta \dot{F}_1 = \frac{K_{p1}}{T_{p1}}\left(\Delta P_{G1} - \Delta P_{D1} - \Delta p_{ac1} - \Delta p_{dc1}\right) - \frac{\Delta F_1}{T_{p1}} \quad (12)$$

$$\Delta \dot{P}_{G1} = -\frac{1}{T_{r1}}\Delta P_{G1} + \left[\frac{1}{T_{r1}} - \frac{k_{r1}}{T_{t1}}\right]\Delta P'_{G1} + \frac{K_{r1}}{T_{t1}}\Delta X_{E1} \quad (13)$$

$$\Delta \dot{P}'_{G1} = -\frac{1}{T_{t1}}\Delta X_{E1} - \frac{1}{T_{t1}}\Delta P'_{G1} \quad (14)$$

$$\Delta \dot{X}_{E1} = -\frac{1}{T_{g1}}\Delta X_{E1} + \frac{1}{T_{g1}}\Delta P_{c1} - \frac{1}{T_{g1}R_1}\Delta F_1 \quad (15)$$

$$ACE_1 = \beta_1 \Delta F_1 + \Delta P_{ac1} + \Delta P_{dc1} \quad (16)$$

$$\Delta \dot{P}_{ac1} = 2\pi T_{12}\left(\Delta F_1 - \Delta F_2\right) \quad (17)$$

$$\Delta P_{dc1}(s) = \frac{K_{dc}}{T_{dc}}\Delta F_1 - \frac{1}{T_{dc}}\Delta_{pdc_1} \quad (18)$$

$$\Delta \dot{F}_2 = \frac{K_{p2}}{T_{p2}}\left(\Delta P_{G2} - \Delta P_{D2} - \Delta P_{ac2} - \Delta P_{dc2}\right) - \frac{\Delta F_2}{T_{p2}} \quad (19)$$

$$= \frac{k_{p2}}{T_{p2}}\left(\Delta P_{G2} - \Delta P_{D2} - a_{12}\Delta P_{ac1} - a_{12}\Delta P_{dc1}\right) - \frac{\Delta F_2}{T_{p2}} \quad (20)$$

$$\Delta \dot{P}_{G2} = -\frac{1}{T_{r2}}\Delta P_{G2} + \left[\frac{1}{T_{r2}} - \frac{k_{r2}}{T_{t2}}\right]\Delta P'_{G2} + \frac{K_{r2}}{T_{t2}}\Delta X_{E2} \quad (21)$$

$$\Delta \dot{P}'_{G2} = -\frac{1}{T_{t2}}\Delta X_{E2} - \frac{1}{T_{t2}}\Delta P'_{G2} \quad (22)$$

$$\Delta \dot{X}_{E2} = -\frac{1}{T_{g2}}\Delta X_{E2} + \frac{1}{T_{g2}}\Delta P_{c2} - \frac{1}{T_{g2}R_2}\Delta F_2 \quad (23)$$

3.4 Integral Squared Error Criterion

In order to ensure zero steady state error condition an integral controller may suitability designed for the augmented system. To incorporate the integral function in the controller, the system equations (1) and (2) are augmented with new state variables defined as the integral of $ACE_i \left(\int v_i dt\right), i = 1,2,...N$.

The augmented system of the order $(N+n)$ may be described as

$$\dot{\bar{x}} = \bar{A}\bar{x} + \bar{B}u + \bar{\Gamma}d \quad (24)$$

$$\bar{x} = \begin{bmatrix} \int vdt \\ x \end{bmatrix} \begin{matrix} \}N \\ \}n \end{matrix} \quad (25)$$

Where

$$\bar{A} = \begin{bmatrix} 0 & C \\ 0 & A \end{bmatrix} \bar{B} = \begin{bmatrix} 0 \\ B \end{bmatrix} \text{ and } \bar{\Gamma} = \begin{bmatrix} 0 \\ \Gamma \end{bmatrix}$$

The problem now is to design the decentralized feedback control law

$$u_i = -k_i^T \bar{y}_i \qquad i = 1,2\ldots..,N \quad (26)$$

The control law equation may be written in-terms of v_i as

$$u_i = -k_i \int v_i dt \qquad i = 1.2\ldots..,N \quad (27)$$

where k_i is the integral feedback gain vector**.**

Controllers designed on the basis of ISE criterion ensure reduction of rise time to limit the effect of large initial errors, reduction of peak overshoot and reduction of settling time to limit the effect of small errors lasting for a long time [20]. Further, this criterion is often of practical significance because of the minimization of control effort. The conventional decentralized optimum proportional plus integral controllers are designed using output feedback for the above mentioned case studies.

The following quadratic performance index is considered to obtain the optimum decentralized controller output feedback proportional plus integral gains for the interconnected two-area (identical areas) thermal reheat power system $\left(k_{1i} = \cdots = k_{2i}\right)$.

$$J_i = \int_0^t \left(x_{ei}^T W_i \, x_{ei}\right) dt \qquad i = 1, 2 \qquad (28)$$

Where $W_i = diag\{w_{i1,} w_{i2}\}$ and $x_{ei}^{\;T} = [\Delta f_i, \Delta \dot{p}_{ei}]$

w_{i1} and w_{i2} are weighting factors for the frequency deviation and tie–line power deviation respectively of area i.

4. Design of Fuzzy Logic Systems

Fuzzy logic systems belong to the category of computational intelligence technique One advantage of the fuzzy logic over the other forms of knowledge-based controllers lies in the interpolative nature of the fuzzy control rules. The overlapping fuzzy antecedents to the control rules provide transitions between the control actions of different rules. Because of this interpolative quality, fuzzy controllers usually require far fewer rules than other knowledge-based controllers [7,8].

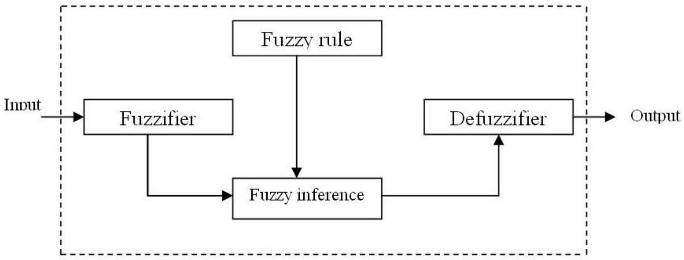


Figure 4. Block diagram of fuzzy logic controller

A fuzzy system knowledge base consists of a fuzzy if then rules and membership functions characterizing the fuzzy sets. The block diagram and architecture of fuzzy logic controller is shown in fig4. Membership function (MF) specifies the degree to which a given input belongs to a set. Here triangular membership function have been used to explore best dynamic responses namely negative big(NB), negative small(NS) , zero(ZE), positive small (PS), positive big(PB). Fuzzy rules are conditional statement that specifies the relationship among fuzzy variables. These rules help to describe the control action in quantitative terms and have been obtained by examining the output response to the corresponding inputs to the fuzzy controllers. Defuzzification, to obtain crisp value of FLC output is done by centre of area method. The fuzzy rules are designed as shown in table 1.

Table 1. Fuzzy Logic Rules For LFC

ACE / $\dot{ACE}$	**NB**	**NS**	**Z**	**PS**	**PB**
NB	NB	NB	NS	NS	ZE
NS	NB	NB	NS	ZE	ZE
Z	NS	NS	ZE	PS	PS
PS	ZE	NS	PS	PS	PB
PB	ZE	ZE	PS	PB	PB

5. Two Layered Fuzzy Logic Controller

The aim of introducing two layered fuzzy logic controller [15] is to eliminate the steady state error and improve the performance of the output response of the system under study. The proposed control scheme is shown in Fig. 5. The controller consists of two "layers": a fuzzy pre-compensator and a usual fuzzy PI controller. The error e(k) and change of error Δe(k) are the inputs to the precompensator. The output of the pre-compensator is μ(k) The PI Controller is usually implemented as follows:

$$u(k) = k_p e(k) + TK_i \sum_{n=0}^{k} e(n) \qquad (29)$$

Where $e(k) = y(k) - y_r(k)$ and Δ e(K) = e (k) - e(k-1)

The controller output, process output and the set point are denoted as u, y and y_r respectively. Experience-based tuning method - Ziegler-Nichols method which widely adopted [16] requires a close attention since the process has to be operated near instability to measure the ultimate gain and period. This tuning technique may fail to tune the process with relatively large dead time [16]. In order to improve the performance of PI tuning a number of attempts have been made which can be categorized into two groups: Set point modification and gain modification.
The set point modification introduces new error terms

$$e_p = y_r(k) F_p(e, \Delta e) - y(k) \qquad (30)$$

$$e_i = y_r(k) F_i(e, \Delta e) - y(k) \qquad (31)$$

The corresponding control law is given by, Where F_p , F_i are non linear functions of e and Δe.

$$u(k) = k_p e_p(k) + TK_i \sum_{n=0}^{k} e_i(n) \qquad (32)$$

As a special case, one would like to modify the set point only in proportional terms. This implies F_p =β ; F_i =1 set point weight [17]

$$\therefore \text{U(k)} = K_p\{\beta y_r(k) - y(k)\} + TK_i \sum_{n=0}^{k} e(n) \qquad (33)$$

or

$$U(k) = K_p e'(k) + TK_i \sum_{n=0}^{k} e'(n)$$

The pre-compensation scheme [17, 18] is easy to implement in practice, since the existing PI control can be used without modification in conjunction with the fuzzy pre-compensator as shown in Figure. 5(a).

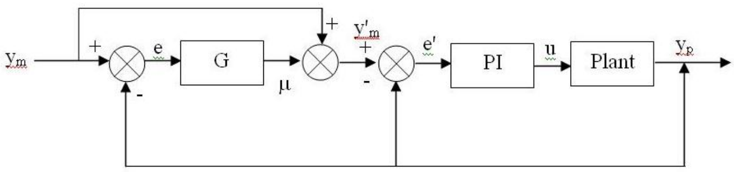


Figure 5. Basic structure of fuzzy pre-compensated PI controller

The procedure of rule generation consists of two parts (i) learning of initial rules which determines the linguistic values of the consequent variables. (ii) fine tuning adjusts the membership function of the rules obtained by the previous step. The structure of the pre-compensation rule is written as If e is L_e, and Δe is LΔe then C is L_c where L_e, ΔL_e and L_c are linguistic values of e, Δe, c respectively.
Each fuzzy variable is assumed to take 5 linguistic values Le, LΔe, or Lc = {NB, NS, ZE, PS, PB} this leads to fuzzy rules, if the rule base is complete.

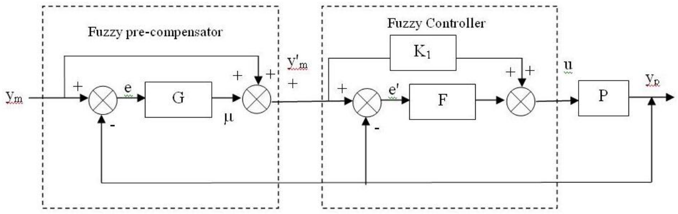


Figure 5 (a). Proposed two layered fuzzy logic controller

The dynamics of overall system is than described by following equations

$$e(k) = ym(k) - yp(k) \quad (34)$$

$$\Delta e(k) = e(k) - e(k-1) \quad (35)$$

$$\mu(k) = G[e(k), \Delta e(k)] \quad (36)$$

Where μ(k) is a compensating term which is generated using a fuzzy logic scheme

$$y'_m(k) = y_m(k) + \mu(k) \quad (37)$$

$$e'(k) = y'_m(k) + y_p(k) \quad (38)$$

$$\Delta e'(k) = e'(k) - e'(k-1) \quad (39)$$

The proposed two layered FLC compensate these defects and gives fast responses without large overshoot and/or undershoot. Moreover to steady state error reduces to zero. The first layer fuzzy pre compensator is used to update and modify the reference value of the output signals to damp out oscillations. The fuzzy states of the input and output all are chosen to be equal in number and use the same linguistic descriptors as N = Negative, Z = Zero, P = Positive to design the fuzzy rules. The fuzzy logic rules for precompensator are presented in Table-2.

Table 2. Fuzzy Logic Rules for Precompensator

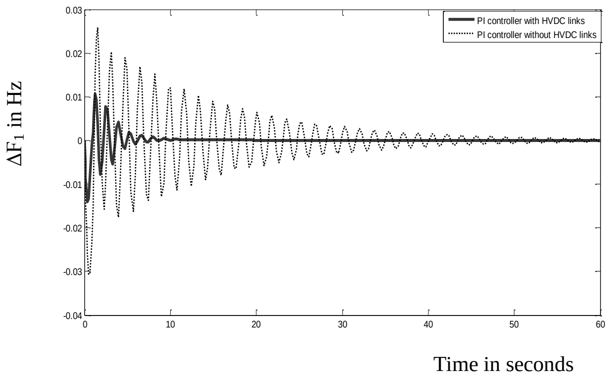
$\dot{ACE}$ \ ACE	N	Z	P
N	N	N	N
Z	Z	Z	Z
P	Z	P	P

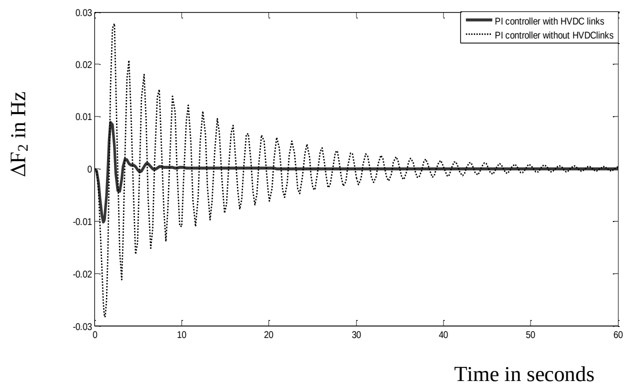
The second layer which is known as feedback fuzzy logic control reduces the steady state error to zero. The output of the FLC is given by

$$u(k) = K_1 y'_m(k) + F[e'(k), \Delta e'(k)] \quad (40)$$

6. Simulations Results and Observations

The optimal gains of the conventional PI controller are determined on the basis of Integral Squared Error (ISE) technique by minimizing the quadratic performance index. This controller is implemented in the interconnected two area power systems without and with HVDC link for 1% step load disturbance in area 1. The conventional optimum gain values are found to be $K_{P1}=K_{P2}=1.3$ and $K_{I1}=K_{I2}=0.08$ for the two area interconnected power system without HVDC link, $K_{p1}=K_{p2}=2.1$ and $K_{i1}=K_{i2}=0.25$ with HVDC link. Moreover the fuzzy logic and two layered fuzzy logic controller are designed and implemented in the interconnected two area power system without and with HVDC link for 1% step load disturbance in area 1. Simulations results are shown in fig 6(a) and 6(b). It is found that the proposed two layered fuzzy logic controller has less over/ undershoots and ensures faster settling time and improvement in stability as compared with fuzzy logic controller and conventional PI controller.





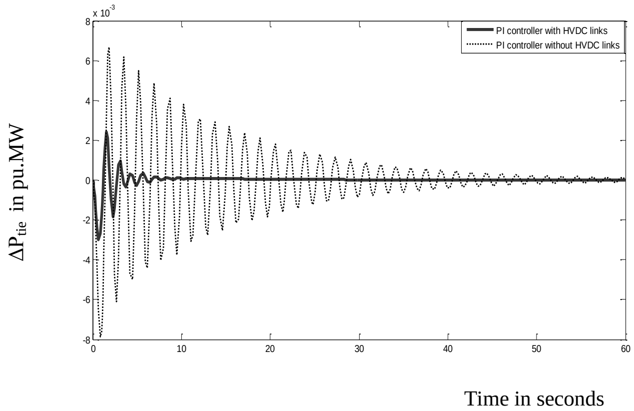


Figure 6(a). Dynamic responses of the frequency deviation and tie-line power deviations for two area thermal reheat power system with and without HVDC links considering 0.01 pu MW step load disturbance in area 1using PI controllers

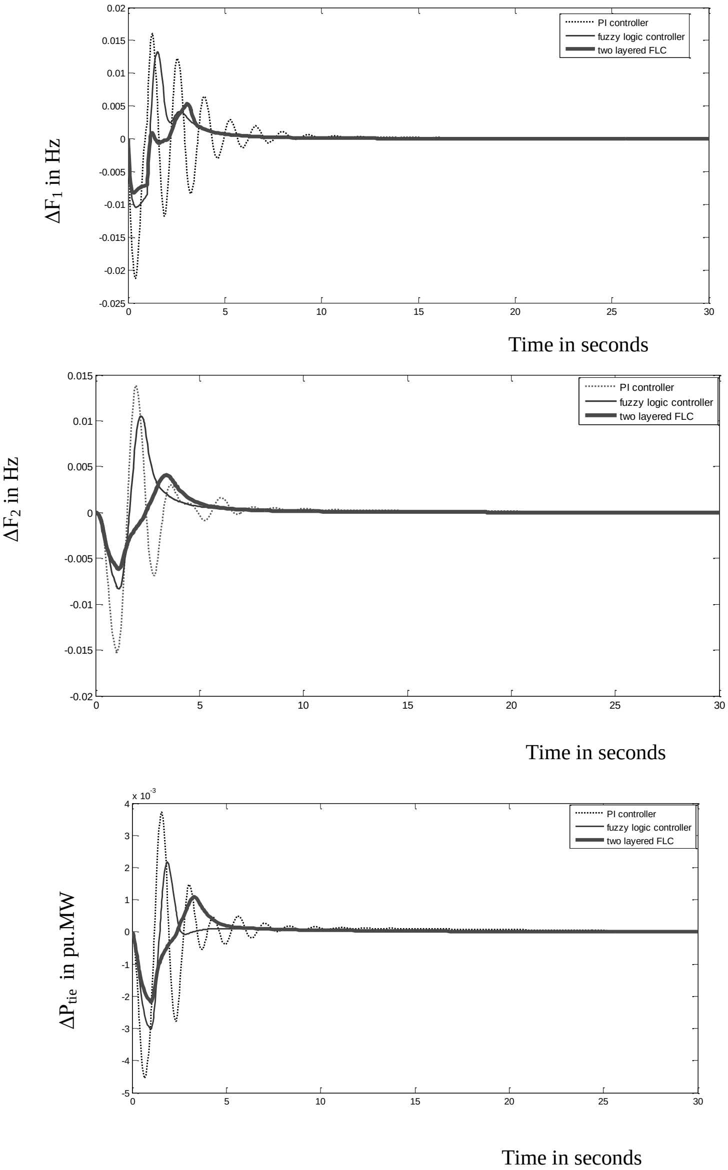


Figure 6(b). Comparison of the dynamic responses of the frequency deviations and tie line deviation for two area thermal reheat power system with HVDC links considering 0.01 pu.MW step load disturbance in area 1.

Conclusion:

In this paper, the conventional PI controllers are designed and implemented in a two-area thermal reheat power system interconnected with AC tie-line and with AC/DC hybrid tie-lines. From the dynamic response reveals that the two-area reheat power system when interconnected with AC/DC hybrid tie-line ensures far for better transient performance and faster settling time than that of the system with ac tie-lines. Moreover, the fuzzy PI controller and two layered fuzzy PI controllers were designed and implemented in the two area thermal reheat power system interconnected with ac/dc hybrid tie-line. The Dynamic responses of the system with these controllers are compared and it is found that the two layered fuzzy PI controllers are found to be the best among the three controllers as the two layered fuzzy PI controller exhibits very less frequency oscillations, very less tie-line power deviations and also very less control effort.

Acknowledgement:

The authors wish to thank the authorities of Annamalai University, Annamalainagar, Tamilnadu, India for the facilities provided to prepare this paper. The authors also wish to thank Dr. M.M.T.Ansari, Associate Professor, Department of Electrical Engg., Annamalai University, for the valuable suggestions in carrying out this paper

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Appendix:

(i) Data for Thermal Power System with Reheat Turbines [11].

f^0 = 60 Hz, $PR_1 = PR_2$ = 2000 MW, $K_{p1}=K_{p2}$= 120 Hz / pu.MW, $T_{pS1} = T_{pS2}$ = 20 sec, $T_{t1} = T_{t2}$ = 0.3 sec, $T_{g1}=T_{g2}$= 0.08 sec, $K_{r1}=K_{r2}$= 0.5, $T_{r1} = T_{r2}$ = 10 sec, R1 = R2 = 2.4 Hz/p.u MW, $\beta_1=\beta_2$ = 0.425 pu.MW/Hz, ΔP_{D1} = 0.01 p.u MW, T = 2 sec (Normal sampling rate),

(ii) Data for AC link [14]

P_{tmax} 200 MW; T_{12}=0.545 pu.MW/Hz

(iii) Data for DC link [14]

K_{dc}=1.0; T_{dc}= 0.5 sec

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