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Load Frequency Control of Two-area Interconnected Power System Using Optimal Controller, PID Controller and Fuzzy Logic Controller

[1]Basavarajappa S R, [2]Dr M S Nagaraj
[1,2] Department of Electrical and Electronics Engineering, BIET, Davanagere, Karnataka
E-mail: basavarajsr@gmail.com, msndvg@gmail.com

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Abstract
In this paper, decentralized control scheme for Load Frequency Control (LFC) problem in a two-area interconnected power system with Fuzzy Logic Controller (FLC) is presented and its performance is compared with that of Optimal Controller (OC) and Proportional-Integral-Derivative (PID) Controller used in the same power system. This control scheme is simulated in MATLAB-Simulink for a two-area interconnected power system consisting of two generating units with non-reheat turbines to highlight the performance in terms of robustness and optimality. The step response of these control schemes against step load change is analysed and compared.

Keywords
Load Frequency Control, Interconnected Power System, Optimal Controller, PID Controller, Fuzzy Logic Controller.

Introduction
In energy control centres, two main areas of concern for generation control on large, interconnected power systems are: Automatic Generation Control (AGC) and Economic Load Dispatch. Main functions of AGC are to maintain the desired MW output to balance the generation and load, to maintain the nominal frequency and to maintain the net interchange of real power through tie-lines between control areas at scheduled values. AGC computes the Area Control Error (ACE) defined as net real power interchange together with a gain, called the frequency bias, as a multiplier on the frequency deviation and also changes the output set point position of the generators within the area, so as to keep the ACE at a very low value, near to zero [1, 2].
In the operation and control of interconnected power systems, problem of controlling the real power output of the synchronous generators in response to changes in system frequency and tie-line power interchange within specified limits is known as Load Frequency Control (LFC) [3]. A number of control strategies like optimal controller, PID controller, have been employed in the design of load frequency controllers, in order to achieve better dynamic performance. With the recent technological developments, Artificial Intelligent controllers have been replacing and overcoming the drawbacks of conventional Proportional-Integral (PI) controllers. Moreover, recently intelligent approaches, like FLC and Fuzzy-PID controllers are being applied for optimal load frequency controller design.

Load Frequency Controllers
Generally, LFC in AGC is systematically arranged in two different levels [3]: Primary control is provided by the speed governor on each of the synchronous generators, which provide automatic control action to sudden change of load, and Secondary control is provided by the LFC loop with the conventional or modern controller to keep ACE to zero. The objectives of LFC are to minimize the transient deviations in system frequency and tie-line power interchange and to ensure their steady state errors to be zeros, under unexpected external disturbances. In addition, the LFC has to be robust against disturbances and parameter uncertainties. In order to achieve the objectives, the following types of controllers are used in a two-area interconnected power system, whose block diagram with single time constant transfer functions of governor, turbine, generator and load as shown in Fig. 1.
The transfer function of an isolated power system with change in load (ΔP_L) as input and change in frequency (Δf) as output is given by

$$G(s) = \frac{\Delta P_L(s)}{\Delta f(s)} = \frac{-R\,B\,K_{ps}(sT_g+1)(sT_t+1)}{R\,(sT_g+1)(sT_t+1)(sT_{ps}+1)+K_{ps}} \tag{1}$$

where, R is the governor speed regulation (Hz/pu MW), B is the frequency bias factor (pu MW/Hz), K_{ps} is the power system gain (Hz/pu MW), T_{ps} is the power system time constant (sec), T_t and T_g are steam turbine and speed governor time constants (sec) respectively.

1. Optimal Controller

Modern control theory is applied in the design of the optimal controller or linear quadratic regulator for the linear systems with quadratic performance index [1, 4]. The aim of this controller design is to obtain a control law $u(x,t)$ which can change the system from its initial state to the final state by minimizing the performance index.

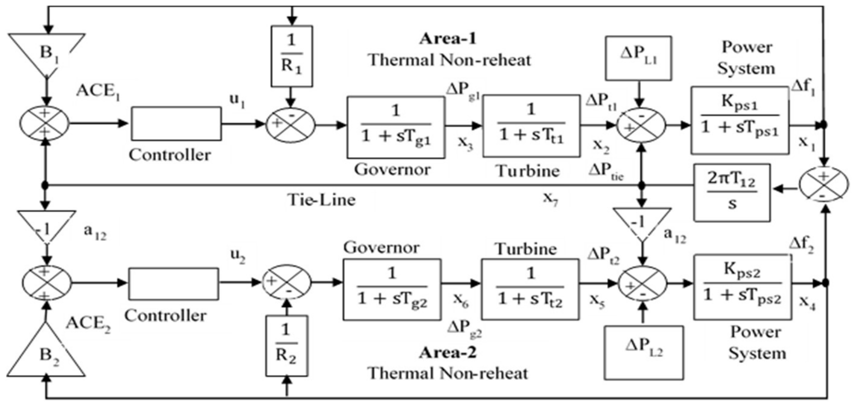

Fig. 1: Two-Area Interconnected Power System

The state space model of the system under consideration is given by

System State Equation: $\dot{x} = Ax + Bu$ (2)

Output Equation: $y = Cx$ (3)

Formulation of the state space model is achieved by writing the differential equations describing each individual block of state space model of two area power system in terms of nine state variables and is given by

$$\dot{x} = Ax + Bu + Fw \tag{4}$$

where $x = [x_1, x_2, \dots x_9]^T$ = State Vector, $u = [u_1 \ u_2]^T$ = Control Vector, $w = [w_1 \ w_2]^T$ = Disturbance Vector.

For full state feedback, the control vector u is constructed by a linear combination of all states, $u = -Kx$, where K is the feedback gain matrix. Using optimal control theory, K is obtained by the solution of the reduced matrix Riccati equation [4, 7] given by

$$A^T S + SA - SBR^{-1}B^T S + Q = 0 \tag{5}$$

where $R^{-1}B^T S =$ K and S is a real, symmetric and positive definite matrix. Q and R can be recognised as symmetric matrices to minimise performance index in quadratic form.

The closed loop equation is $\dot{x} = Ax + B(-Kx) = (A - BK)x = A_c x$ (6)

where $A_c = (A - BK)$ = closed loop system matrix.

For closed loop system stability, all the eigenvalues of the matrix A_c should have negative real parts.

2. PID Controller

Conventional PID controller is widely used in industry because of ease in design and less cost. It is a combination of the Proportional, Integral and Derivative controllers and is used when the system requires improvements in both transient and steady-state conditions. However, if the system is so complicated that its mathematical model cannot be easily obtained, then experimental approaches are used to the tune the PID controller. The controller parameters - proportional gain (K_p), integral gain (K_i) and derivative gain (K_d) can be obtained for a system with feedback [6].

3. Fuzzy Logic Controller

Fuzzy set theory and fuzzy logic set up the rules of a nonlinear system with uncertainty. Fuzzy control is based on a logical system called fuzzy logic which is much closer in determination to knowledge and natural language than classical logic. Fuzzy logic is a knowledge or fuzzy rule-based system [8]. The measured output is a crisp quantity, it can be fuzzified into a fuzzy set, then considered as the fuzzy input into a FLC. The output of the FLC is then another series of fuzzy sets which can be converted into crisp quantities using defuzzification methods. These defuzzified control-output values then become the input values to the power system.

Algorithms for Controllers Design

1. Algorithm for Optimal Controller Design

Step 1: Define the power system parameter values.

Step 2: Write differential equations in terms state variables x_1 to x_9 as shown in the Fig.1.

Step 3: Obtain the state space model with matrices A, B, C, D, Q and R.

Step 4: Solve the Riccati equation for matrices S and K for which the system is stable.

2. Algorithm for PID Controller Design

Step 1: Obtain the Simulink model for a single area with system parameter values.

Step 2: Obtain the value of critical gain (K_{cr}) that results in marginal stability with critical period (P_{cr}) when only proportional control action is used in feedback.

Step 3: Calculate the values of K_p, K_i and K_d using Ziegler and Nichols rules, which give a stable system.

3. Algorithm for Fuzzy Logic Controller Design

Step 1: Define the linguistic variables NB, NM, NS, Z, PS, PM, PB which confirm 7 fuzzy variables for two inputs, ACE and derivative of ACE.

Step 2: Prepare the control rules or FAM table, and enter the 49 fuzzy rules in IF-THEN format.

Step 3: Select the triangular membership functions with rage, Mamdani systems with max–min deductive inference method and centroid method of defuzzification to obtain the fis file.

Step 4: Use this fis file in Fuzzy inference system to train the Fuzzy-PID controller for best performance.

Simulation Results and Discussions

Parameters of the power system are given in Table 1 with base frequency 50 Hz in India [5, 6].

Table 1: Power System Parameter Values

Parameters	P_r	P_L	P_{tie}	f_0	R	D	B	T_g	T_t	H	K_{ps}	T_{ps}	T_{12}	δ
Area-1	2000	1000	200	50	2.5	0.01	0.41	0.2	0.5	5	100	20	0.0866	30
Area-2	2000	1000		50	2.5	0.01	0.41	0.2	0.5	5	100	20		

For optimal controller, the full state feedback gain values obtained from the algorithm are given in Table 2.

Table 2: Full State Feedback Gain Values

K_{11}	K_{12}	K_{13}	K_{14}	K_{15}	K_{16}	K_{17}	K_{18}	K_{19}
0.4835	1.0697	0.3611	- 0.0681	- 0.1924	- 0.0565	- 0.6570	1.0000	0.0000
K_{21}	K_{22}	K_{23}	K_{24}	K_{25}	K_{26}	K_{27}	K_{28}	K_{29}
- 0.0681	- 0.1924	- 0.0565	0.4835	1.0697	0.3611	0.6570	0.0000	1.0000

For PID controller, the parameters K_p, K_i and K_d values obtained from the algorithm for fine tuning are given in Table 3.

Table 3: PID Controller Parameters

K_{cr}	P_{cr}	$K_p = 0.6\, K_{cr}$	$K_i = 1.2\left(\frac{K_{cr}}{P_{cr}}\right)$	$K_d = 0.075(K_{cr}\, P_{cr})$
0.6295	5.5	0.3777	0.1373	0.2597

For Fuzzy logic controller FAM table is given in the Table 4 and control surface obtained from the algorithm is shown in Fig. 2.

Table 4: Control Rules or FAM table

Rule Bases		Derivative Error						
		NB	NM	NS	Z	PS	PM	PB
Error (ACE)	NB	PB	PB	PM	PM	PS	PS	Z
	NM	PB	PM	PM	PM	PS	Z	Z
	NS	PB	PM	PM	PM	Z	NS	NS
	Z	PB	PM	PM	Z	NS	NM	NB
	PS	PM	PM	NS	NS	NM	NB	NB
	PM	PM	PS	NS	NM	NB	NM	NB
	PB	NS	NS	NM	NM	NM	NM	NB

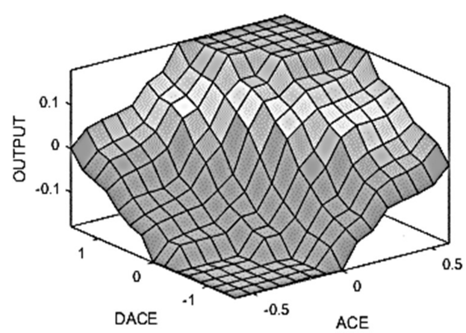

Fig. 2: Control Surface of fis.

The simulation of the power system model shown in Fig. 1 with system parameters and different controllers is done using MATLAB-Simulink. Two cases of change in load powers are considered.

Case 1: The Change in Load Powers: ΔP_{L1} = 0.01 pu and ΔP_{L2} = 0 pu.

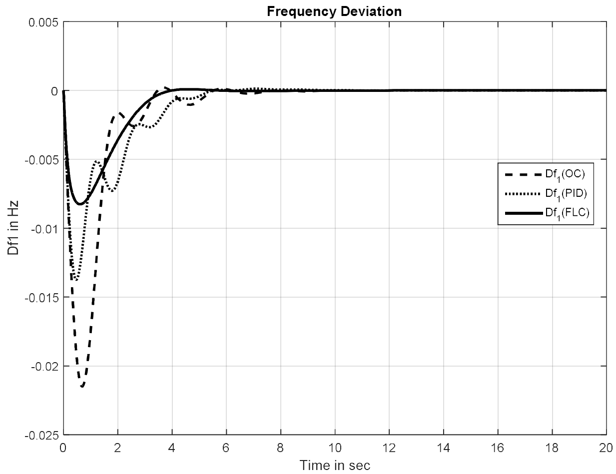

Fig. 3: Frequency Deviation in Area-1 with 1% Load Increase in Area-1

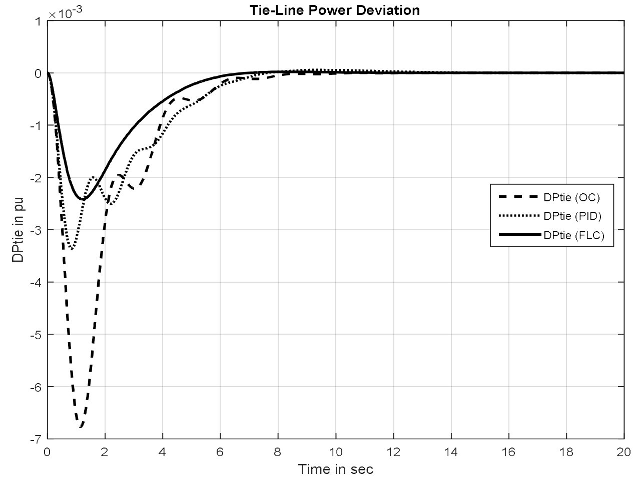

Fig. 4: Tie-Line Power Deviation with 1% Load Increase in Area-1

Table 5: Time Response Specifications for Δf_1

Sl. No.	Controllers	M_p in Hz	t_s in sec	Response
1	Optimal	- 0.0215	5.2104	Stable
2	PID	- 0.0137	5.1516	Stable
3	FL	- 0.0083	3.6809	Stable

Table 6: Time Response Specifications for ΔP_{tie}

Sl. No.	Controllers	M_p in pu	t_s in sec	Response
1	Optimal	- 0.0068	6.2293	Stable
2	PID	- 0.0034	7.0614	Stable
3	FL	- 0.0024	6.2005	Stable

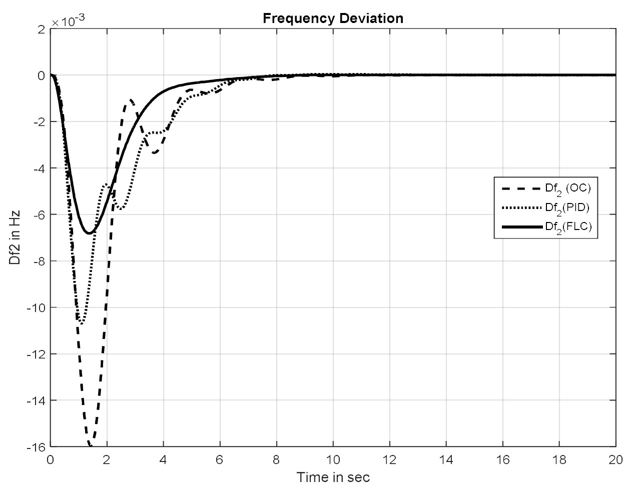

Fig. 5: Frequency Deviation in Area-2 with 1% Load Increase in Area-1

Table 7: Time Response Specifications for Δf_2

Sl. No.	Controllers	M_p in Hz	t_s in sec	Response
1	Optimal	- 0.0160	6.4186	Stable
2	PID	- 0.0107	6.6669	Stable
3	FL	- 0.0068	6.7261	Stable

Figs. 3 to 5 compare the frequency deviations and tie-line real power deviation with optimal controller, proportional-integral-derivative controller and fuzzy logic controller. Tables 5 to 7 presents the measured time response specifications. In dynamic condition as the load increases in area-1, system frequency decreases in both areas and tie-line real power flows from area-2 to area-1 till the supplementary control action of area-1 balances its generation and load. In the steady state condition, these deviations $(\Delta f_1, \Delta P_{tie}, \Delta f_2)$ reduced to zero. From the simulation results, it can be observed that, Fuzzy logic tuned with PID controller gives the transient response with low undershoot (M_p), less settling time (t_s), and zero steady state error, while the performance of Z-N tuned PID controller is better than the optimal controller.

Case 2: The Change in Load Powers: ΔP_{L1} = 0.02 pu and ΔP_{L2} = 0.01 pu.

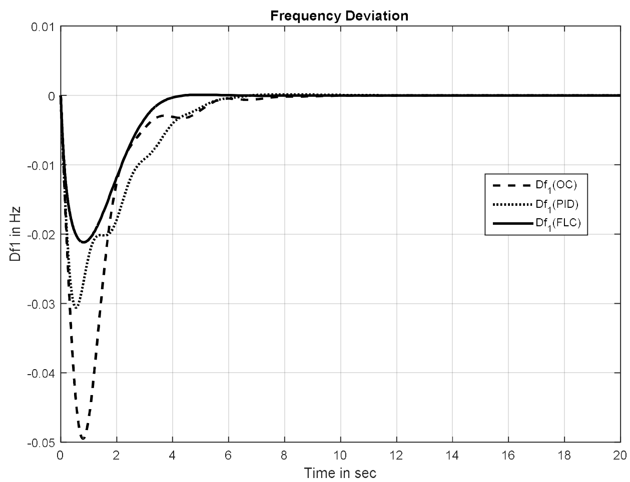

Fig. 6: Frequency Deviation in Area-1 with 2% Load Increase in Area-1 and 1% Load Increase in Area-2

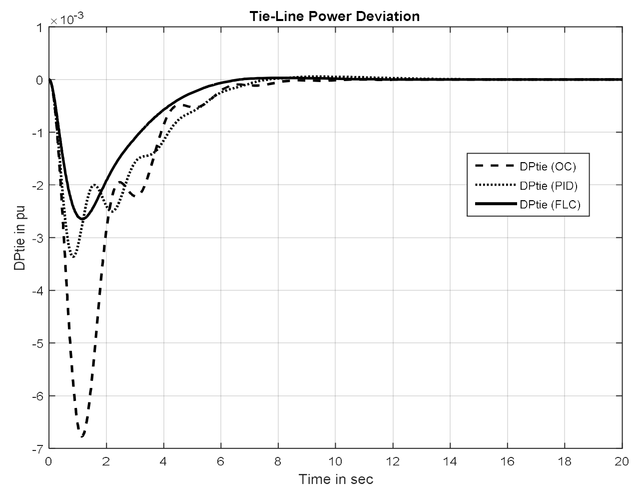

Fig. 7: Tie-Line Power Deviation with 2% Load Increase in Area-1 and 1% Load Increase in Area-2

Table 8: Time Response Specifications for Δf_1

Sl. No.	Controllers	M_p in Hz	t_s in sec	Response
1	Optimal	- 0.0495	5.4367	Stable
2	PID	- 0.0306	5.6672	Stable
3	FL	- 0.0212	3.9001	Stable

Table 9: Time Response Specifications for ΔP_{tie}

Sl. No.	Controllers	M_p in pu	t_s in sec	Response
1	Optimal	- 0.0068	6.2521	Stable
2	PID	- 0.0034	7.0621	Stable
3	FL	- 0.0026	6.0965	Stable

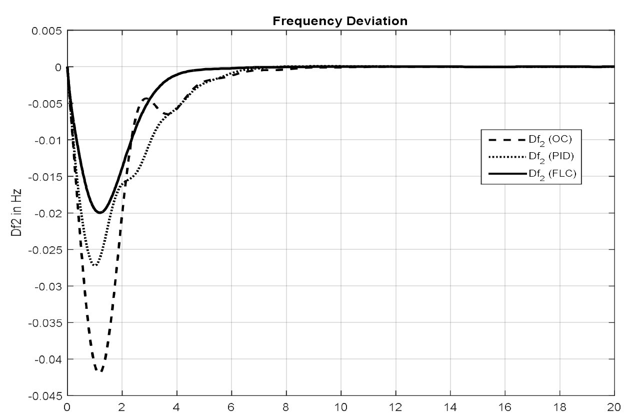

Fig. 8: Frequency Deviation in Area-2 with 2% Load Increase in Area-1 and 1% Load Increase in Area-2

Table 10: Time Response Specifications for Δf_2

Sl. No.	Controllers	M_p in Hz	t_s in sec	Response
1	Optimal	- 0.0419	6.3539	Stable
2	PID	- 0.0272	6.3206	Stable
3	FL	- 0.0200	4.8607	Stable

Figs. 6 to 8 show the simulation results of the same power system model for case-2. Tables 8 to 10 presents the measured time response specifications with load power changes in both the areas. As the load increase in area-1 is more than that in area-2, system frequency deviates and tie-line real power flows from area-2 to area-1 to balance the generation and load. In steady state condition, the ACE reduced to zero due to supplymentary control action. After tuning the controllers, it can be found that, FLC tuned with PID controller gives the stable transient responses with less undershoot and settling time than the other two controllers.
The values of undershoot and settling time obtained from simualtion for the above two cases with Fuzzy-PID controller action are very small and the time responses are fast campared to their values and responces given in the references [6-12].

Conclusion

In the interconnected power systems, it is necessory to maintain the system frequency to its nominal value and the tie-line real power as close as possible to its scheduled value when the load changes. LFC model of a two-area interconnected power system has been developed with same area characteristics for optimal control, conventional control and fuzzy logic control techniques. In this paper the performance of three controllers designed for LFC problem is simulated using MATLAB-Simulink tools. Based on the simulation results obtained, it is clear that with the proper tuning of controller parameters, the system frequency deviation and the tie-line real power deviation could brought to zero, when sudden changes in load occurs. It is seen from the comparison of performance of controllers used, Fuzzy logic tuned controller gives the best performance with zero steady state error, minimum undershoot and less settling time than optimal controller and conventional PID controller.

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