Automatic Generation Control with Fuzzy-Proportional Integral Controller in an Isolated Power System Considering Governor Nonlinearity

M. F. Hossain*, T. Takahashi**, M.G. Rabbani***

Abstract

This paper presents the implementation of Fuzzy-Proportional Integral controller (FPIC) for controlling automatic generation control (AGC) in electric power generation systems. A typical single area power system is considered with governor nonlinearity. As a consequence of continually load variation, the frequency of the power system changes over time. In conventional studies, frequency transients are minimized by using conventional proportional integral (PI) controllers aiming of secondary control in AGC and zero steady-state error is obtained after sufficient delay time. In this paper, instead of this method, the configurations of FPIC controller is proposed. In this paper, fuzzy logic control is used to tune the output of the conventional PI controller for getting better performance. For any load changes, the proposed controller restores the frequency to its nominal value within the shortest possible time. This controller provides a satisfactory balance between frequency overshoot and transient oscillations with zero steady-state error. All the results of the proposed controller are compared with conventional PI controller in both cases with and without governor dead-band.

Keywords : Power generation, automatic generation control, Fuzzy-proportional Integral controller, conventional proportional integral controller, fuzzy logic controller, governor dead-band.

---

* *Department of Electrical & Electronic Engineering, Graduate School of Science and Engineering for Research, University of Toyama, 3190 Gofuku, Toyama 930-8555, Toyama, Japan*

** *Department of Electrical & Electronic Engineering, Rajshahi University of Engineering & Technology, Rajshahi-6204, Bangladesh*

*** *Corresponding Author*
E-Mail : m0671047@ems.u-toyama.ac.jp

1. Introduction

Power system stability issue has been studied widely [1]. The dynamic behavior of many industrial plants is heavily influenced by disturbances and, in particular, by changes in operating point [2]. Automatic generation control (AGC) is a very important issue in power system operation and control for supplying sufficient and reliable electric power with good quality [2, 3]. The main goal of the AGC is to minimize the transients deviations and to provide zero steady state errors for frequency deviation in a single area power system [2-4]. Many investigations in the area of automatic generation control (AGC) of isolated and of interconnected power systems have been reported in the past and a number of control strategies have been proposed to achieve improved performance. The conventional control strategy for the LFC problem is to take the integral of control error as the control signal. The proportional integral (PI) control approach is successful in achieving zero steady-state error in the frequency of the system, but it exhibits relatively poor dynamic performance as evidenced by large overshoot and transient frequency oscillations. Moreover, the transient settling time is relatively large [5].

In order to improve the transient response, advanced control techniques have been proposed, which include linear feedback optimal control, adaptive control, and variable structure control [3]. In the application of optimal control techniques, the controller design is normally based on a fixed parameter model of the system derived by a linearization process. Power system parameters are a function of the operating point. Therefore, as the operating conditions change, system performance with controllers designed for a specific operating point most likely will not be satisfactory. Consequently, the nonlinear nature of the load frequency control (LFC) problem makes it difficult to ensure stability for all operating points when an integral or a PI controller is used [3, 5]. More recently, fast acting artificial neural networks (ANN) have been developed. But the ANN approach has many inherent drawbacks like requiring of large historical database for proper training, network topology dependence and choice of proper response functions etc due to which exactly similar performance may not be obtained. In order to improve the transient response, an intelligent controller for the LFC problem is developed and applied in connection with the power system under study [5].

The AGC based on fuzzy-PI type controller is proposed in this study. One of its main advantages is that controller parameters can be changed very quickly by the system dynamics because no parameter estimation is required in designing controller for nonlinear systems. Therefore, a fuzzy logic (FLC), which represents a model-free type of nonlinear control algorithms, could be a reasonable solution. The comparative simulation results for a single area power system are presented and discussed in both cases considering governor dead-band (DB).

2. Model of AGC in a Single-Area Power System

The primary Load Frequency Control (LFC) loop depends on the governor speed regulation, a change in the system load will result in a steady-state frequency deviation,. In order to reduce the frequency deviation to zero, a reset action must be provided. The reset action can be achieved by introducing an integral controller to act on the load reference setting to change the speed set point. The integral controller gain K_I must be adjusted for a satisfactory transient response [6]. In a single power system, load frequency control (LFC) equipment is installed for each generator. The controllers are set for a particular operating condition and take care of small changes in load demand to maintain the frequency within the specified limit [1].

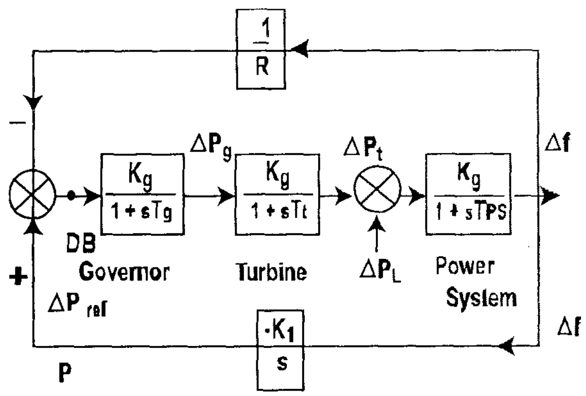


Fig. 1: Model of LFC for a typical single area power system with a conventional PI controller only.

Figure 1 shows a well known block diagram used for AGC of a typical single-area power system along with a conventional PI controller only. The dynamic model equations of a single area power system are given in below:

$$\Delta \dot{f}(t) = \left[K_{PS}\{\Delta P_t(t) - \Delta P_L(t)\} - \Delta f(t)\right]/T_{PS} \tag{1}$$

$$\Delta \dot{P}_t(t) = \left[K_t \Delta P_g(t) - \Delta P_t(t)\right]/T_t \tag{2}$$

$$\Delta \dot{P}_g(t) = \left[K_g\left\{\Delta P_{ref}(t) - \Delta f(t)/R\right\} - \Delta P_g(t)\right]/T_g \tag{3}$$

$$\Delta \dot{P}_{ref}(t) = -K_I \Delta f(t) \tag{4}$$

where, K_I is the Integral controller gain value in p.u. The gain constant K_I controls the rate of investigation, and thus the speed of response of the loop.

The dynamic models in state-space variable form of the above Fig.1 is

$$\dot{X} = AX + BU, \quad Y = CX \tag{5}$$

Where, $X = [\Delta f \;\; \Delta P_t \;\; \Delta P_g \;\; \Delta P_{ref}]^T; U = [\Delta P_L]^T; Y = [\Delta f]$ are the state vector, the control vector and the output variables respectively. The values of the elements of the system matrices A, B, and C may be computed from the nominal parameter values [1, 5, 6], given in Table 1. The critical value of K_I of CIC controller is considered as the base value in the design of the proposed fuzzy logic control scheme.

Table 1: Nominal parameters of a typical single-area power system

R [Hz/p.u.MW]	D [p.u.MW/Hz]	K_g	T_g [s]	K_t
2.4	0.00833	1	0.08	1

T_t [s]	K_{PS}	T_{PS} [s]	ΔP_L [p.u.MW]	K_I
0.3	1.2	20	*variable	*see explanation in text

3. Considering Governor Dead-Band

Governor dead-band is defined as the total magnitude of a sustained speed change within which there is no resulting change in valve position [7, 8]. The limiting value of dead-band is specified as 0.06%. It was shown by Concordia et al [9, 10], that one of the effects of governor dead-band is to increase the apparent steady-state speed regulation R. This can be seen from Fig. 6.1 by joining points 1 and 2 and multiplying the slope of this line with 1/R. The slope of the line without governor dead-band is 1. Dead-band is measured by plotting automatically from the motion of the governor elements from the frequency [7, 8]. Steam turbine dead-band measured have been found to be due principally to back-lash in the linkage connecting the servo position to the camshaft, Much of this appears to occur in the rack and pinion used to rotate the camshaft that operates the control valves.

The speed governor dead-band has significant effect on the dynamic performance of load frequency control system; however, little work has been done in this respect. In fact this backlash nonlinearity introduces a time lag associated with the zero in the governor transfer function [7].

The governor dead-band of the form shown in Fig. 2 exists in real systems and is represented by the nonlinear at points marked DB in Fig. 1.

The governor dead-band of the form shown in Fig. 2 exists in real systems and is represented by the nonlinear at points marked DB in Fig. 1.

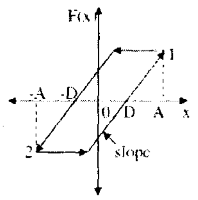
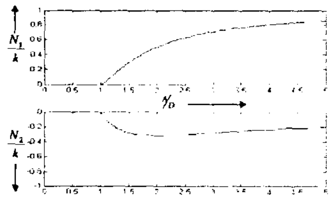
Nonlinearity	Describing Function Coefficients
	$N_1 = \frac{k}{\pi}\left\{\frac{\pi}{2} + \sin^{-1}\left(1 - \frac{2D}{A}\right) + 2\left(1 - \frac{2D}{A}\right)\left[\frac{D}{A}\left(1 - \frac{D}{A}\right)\right]^{1/2}\right\}$ $N_2 = \frac{4kD}{\pi A}\left(1 - \frac{D}{A}\right), A \ge D$ 

Fig. 2: LHS governor dead-band (Backlash) Nonlinearity and RHS Fourier series coefficients of governor dead-band.

Referring to Fig. 2 it is to be noted that the backlash nonlinearity [7, 8, 11] of the hystresis type cannot be completely described by the function F(x) since the output inherently depends on the direction of change in x is positive, the right-hand side of the loop represents the nonlinear characteristics and negative for the other side [7, 8]. Thus adequate description of the hysteresis type of nonlinearity is expressed as

$$y = F(x, \dot{x}) \tag{6}$$

rather than as y = F(x).

To solve this nonlinear problem by the describing function approach, Silzak [11] has shown that it is necessary to make the basic assumption that the variable x, appearing in the non-linear Function $F(x, \dot{x})$ is sufficiently close to a sinusoidal oscillation; that is, $x = A \sin(\omega_0 t)$ (7)

Where the amplitude A and the frequency ω_0, the oscillation are constant. Describing function analysis, therefore, belongs to the methods of solving nonlinear differential equations which are based upon assumed schemes. Such an assumption is quite realistic nonlinear system which may exhibit periods of oscillations arbitrarily close to a pure sinusoid. Also Kimbark [7, 8] has shown that the phasor variables can be treated as state variables in the time domain for small changes.

If the variable x in the nonlinear assumption $F(x, \dot{x})$ has the sinusoidal form shown in equation (7), then the variable $F(x, \dot{x})$ is generally complex, but is also a periodic form of time.

$$F\left(x, \dot{x}\right) = F^0 + N_1 x + \frac{N_2}{w_0} \dot{x} + ------ \tag{8}$$

To solve this it is a reasonable approximation to consider the first three terms only, corresponding coefficients are:

$$F^0 = \frac{1}{2\pi} \int_0^{2\pi} F(A \sin w_0 t, A w_0 \cos w_0 t) d(w_0 t)$$

$$N_1 = \frac{1}{\pi A} \int_0^{2\pi} F(A \sin w_0 t, A w_0 \cos w_0 t) \sin w_0 t \; d(w_0 t) \tag{9}$$

$$N_2 = \frac{1}{\pi A} \int_0^{2\pi} F(A \sin w_0 t, A w_0 \cos w_0 t) \cos w_0 t \; d(w_0 t)$$

Since the backlash nonlinearity is a symmetrical about the origin, the constant term F^0 in the Fourier series (equation (8)) is zero [7, 8]. The constant terms N_1 and N_2 in (equation (9)) are evaluated and displayed in Fig. 2 for different values of A(t).

The Governor Transfer function with linearized dead-band is derived as follows. This will modify the system matrix.

$$G(s) = \frac{N_1 + \frac{N_2}{w_0} s}{1 + T_g s} \tag{10}$$

A typical value of backlash is 0.06%. However, by referring to the discussion of Concordia et al in reference [7-11], it is found from Fig. 2 that A/D = 4 will imply a backlash of approximately 0.05%. This value of A/D for backlash of 0.05% is chosen for digital simulation results.

Referring to Fig. 2, the following Fourier coefficients are obtained:

$$\frac{N_1}{k} = 0.8 \quad and \quad \frac{N_2}{k} = -0.2 \tag{11}$$

The usual value of slope k of the curve shown in Fig. 2 is 1. Therefore, N_1=0.08 and N_2= −0.2.

A typical value of continuous time response, Fig. 2,

indicates f_0=1/2 Hz

or, $w_0 = 2\pi f_0 = \pi$

These values of Fourier coefficients are substituted in equation (8), giving

$$F(x, \dot{x}) = 0.8x - \frac{0.2}{w} \tag{12}$$

3. Critical gain values of conventional PI Controller:

The tuning of the value of gains K_I at Kp=0 was achieved using a systematic exhaustive search according to the IAET criterion shown in equation (13).

$$J_{fre} = \int_0^T |\Delta f(t)| t \, dt \tag{13}$$

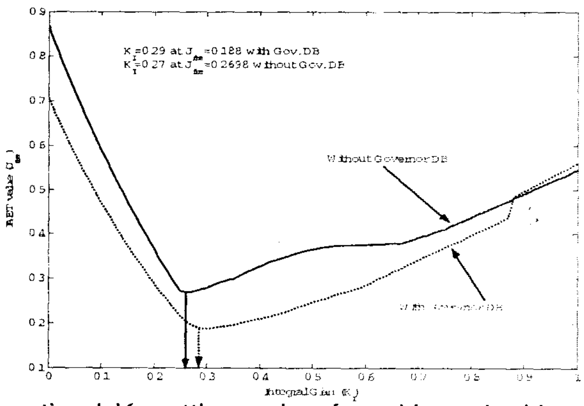


Fig. 3: The optimal K_I setting value for with and without governor dead-band

It is clear from Fig. 3 that in the absence of governor dead-band the best tuned of integral gain value is K_I = 0.29 at J_{fre}=0.188, which is also called the critical value. In the presence of governor dead-band the integral gain value, K_I=0.27 at J_{fre}=0.2698. This K_I value is also calculated by the equation (14) [1].

$$K_I = \frac{1}{4KpsTps}\left(1+\frac{Kps}{R}\right)^2 \tag{14}$$

4. Fuzzy-PI Controller (FPIC)

The general practice in the design of a LFC is to utilize a PI structure. This gives adequate system response considering the stability requirements and the performance of its regulating units. Another approach to this problem, with good results, is the use of modern control theory. Usually, conventional controllers of fixed structure and constant parameters are tuned for one operating condition and can give optimal or suboptimal power system performance for that condition. Since, the characteristics of the power system elements are non-linear, the conventional controllers may not be capable of providing the desired performance for all operating conditions [3, 5] In this case the response of the PI controller is not satisfactory enough and large oscillations may occur in the system. Thus, the integrator gain must be set to a level that provides a compromise between fast transient recovery and low overshoot in the dynamic response of the overall system. Consequently, this type of controller may be relatively slow and not allow the designer to take easily into account possible system non-linearities. Latest efforts are made, as another approach, to develop controllers (based on intelligent control techniques) capable in dealing with such non-linearities and at the same time secure improved system performance [5].

In this paper, instead of this PI controller (shown in Fig. 1), Fuzzy-PI controller is used.. In this controller, the output of PI controller is fuzzyfied by the fuzzy logic controller. Figure 4 shows a typical block diagram for Fuzzy-PI controller [12]. The discrete-time equivalent expression for PI control used in this paper is given as

$$u^*(k) = K_P e^*(k) + K_I T_S \sum_{i=1}^{n} e^*(i)$$

$$\Rightarrow P_{ref}^*(k) = K_P f^*(k) + K_I T_S \sum_{i=1}^{n} f^*(i) \tag{15}$$

$$\Delta e^*(k) \overset{\Delta}{=} e^*(k) - e^*(k-1).$$

$$\Rightarrow \Delta f^*(k) \overset{\Delta}{=} f^*(k) - f^*(k-1) = f_{nom} - f_t \tag{16}$$

The incremental control error at k^{th} instant is given by

$$\Delta u^*(k) = K_P . v^*(k) + K_I . e^*(k-1)$$

$$\Rightarrow \Delta P^*_{ref}(k) = K_P . v^*(k) + K_I . f^*(k-1) \quad (17)$$

Where, $v^*(k)$ is the rate of incremental error,

$$v^*(k) = \frac{[e^*(k) - e^*(k-1)]}{T_s} \quad (18)$$

Where u(k) is the control signal, e(k) is the error between the reference and the process output, T_S is the sampling period for the controller, $\Delta u^*(k)$ is the incremental control effort at k^{th} instant and K_P and K_I are the proportional and integral gains of digital PI controller, respectively.

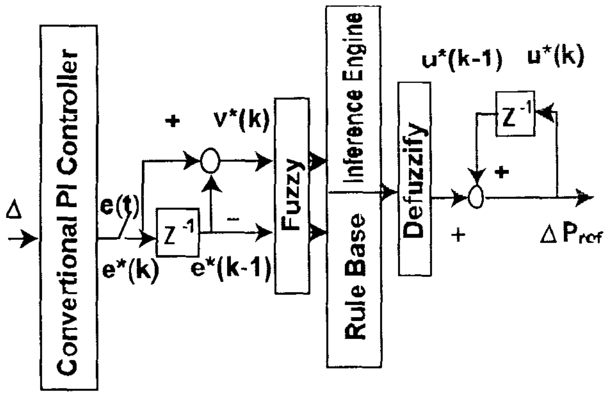


Fig. 4: A typical Fuzzy-PI controller (FPIC).

5. DESIGN STEPS FOR FPIC CONTROLLER

Figure 5 shows a schematic representation of a typical closed-loop fuzzy control system. For the FLC controller, it has been selected two inputs, one is the PI controller output and another is the rate of change of the PI controller output defined as:

$$\text{input1: error} = \Delta u = K_I \int_0^T \Delta f \, dt = e_t \quad (19)$$

$$\text{input2: rate of change in error} = \Delta u = K_I \Delta f = de_t/dt$$

Where, $\Delta f = f_{nom} - f_t$.

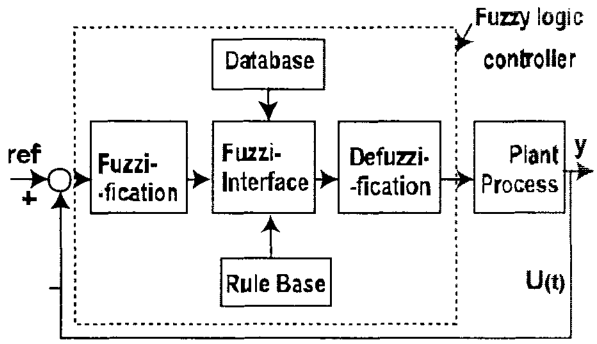


Fig. 5: Block diagram of a typical closed-loop Fuzzy logic controller.

The fuzzy sets of each linguistic variable adopted in this work are: **NB**: Negative Big; **NS**: Negative Small; **Z**: Zero; **PS**: Positive Small; **PB**: Positive Big. The membership functions for the designed FLC controller of the three variables (e_t, de_t/dt, ΔP_{ref}) used are shown in Fig. 6.

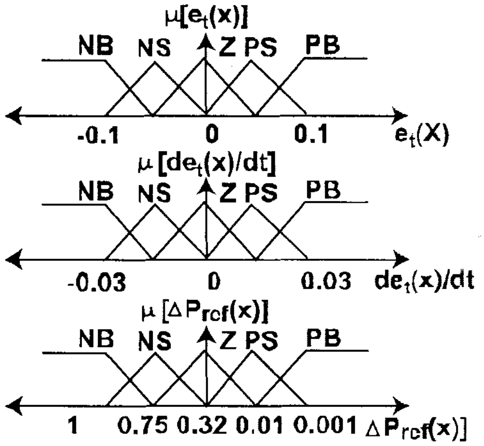


Fig. 6: Membership functions for the fuzzy variable of the proposed FPIC controller.

It is possible to derive a membership value for this variable in many possible ways, one of the rules that has been chosen is

$$\mu(e_t, c\dot{e}_t) = \min\left[\mu(e_t), \mu(de_t/dt)\right] \quad (20)$$

The fuzzy rules are constructing by using trial and error methods. The Output of FPIC controller is given in Table 1.The well-known center of gravity defuzzification method is given by the following expression:

$$\Delta P_{ref} = \sum_{j=1}^{n} \mu_j C_j \Big/ \sum_{j=1}^{n} \mu_j \quad (21)$$

Where, μ_j is the membership value of the linguistic variable and u_j is the precise numerical value.

Table 2: Fuzzy rule base for FPIC controller

e \ $\dot{ce_t}$	NB	NS	Z	PS	PB
NB	NB	NB	NS	Z	Z
NS	NB	NS	Z	Z	PS
Z	NB	Z	Z	PS	PS
PS	Z	Z	PS	PS	PB
PB	Z	PS	PS	PB	PB

6. SIMULATION RESULTS AND DISCUSSION

Computer simulations results based on system non-linear differential equations have been carried out for different load changes. The differential equations have been solved by using the 4th order Range-Kutta method under MATLAB environment. Figure 7, and Fig. 8 depict the simulation results with & without considering the governor DB for step load changes of ΔP_L=0.01, and 0.02 p.u respectively.

In addition of proposed schemes, the damping is improved significantly. In the absence of governor DB, it is evident from the Fig. 7 that 1st peak is significantly improved (50% of the PI controller) and the 3rd and 4th peak of the generator frequency is almost diminished with the proposed mode of control.

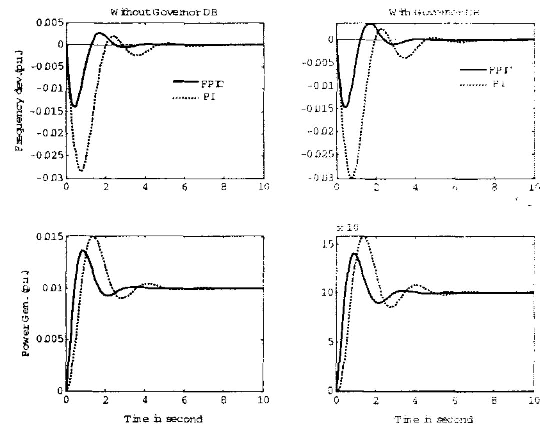


Fig. 7: Frequency deviation, Power generation for the step load change ΔP_L= 0.01 p.u. with & without governor DB

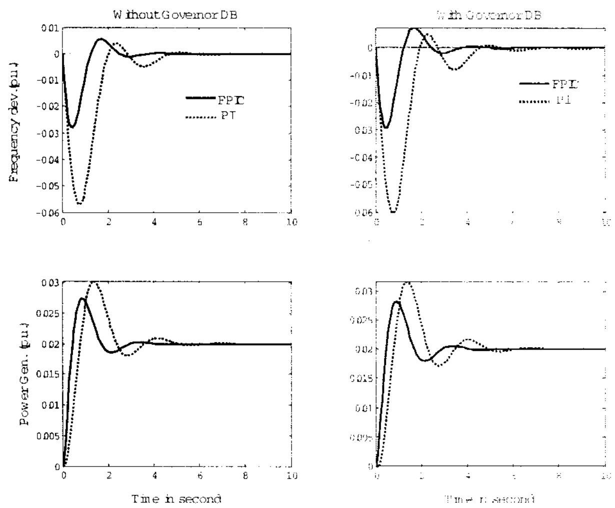


Fig.8: Frequency deviation, Power generation for the step load change $\Delta P_L = 0.02$ p.u. with & without governor DB.

It is clearly shown that considering governor DB 1st peak is greatly reduced 35% of the PI controller and 4th peak is minimized compared with conventional PI controller. Moreover, this eventually reduces the settling time of the frequency for both cases, which in turn brings the Fuzzy-PI controller in more advantageous position for subsequent use.

Fig. 8 shows the system performances with and without governor DB. It is clearly observed that in the absence of governor DB, the results of 1st, 2nd peak & 4th peak are same as shown in Fig. 7 in comparison with PI controller. In the presence of governor DB, 4th peak of the system frequency deviation is almost minimized but PI controller exhibits unstability of the system. Therefore, settling time is greatly reduced in the proposed mode of FPIC controller.
The comparative results for FPIC and PI controller are shown in Table 3 and Fig. 9.

Table 3: Time and 1st peak of frequency deviation

Step load change	Without governor DB		With governor DB	
	FPIC	PI	FPIC	PI
0.01	0.4625s -0.0141	0.82s, -0.0281	0.635s, - 0.0189	0.822s, - 0.0308
0.015	0.4136s, - 0.0211	0.712s, -0.0422	0.8332s, - 0.0399	1.1271s, - 0.0537
0.02	0.4571s, - 0.02816	0.813s,- 0.0562	1.233s, - 0.0691	1.2802s, - 0.0857
0.05	0.463s, - 0.07034	0.724s, -0.141	2.803s, - 0.4033	2.771s, - 0.4316

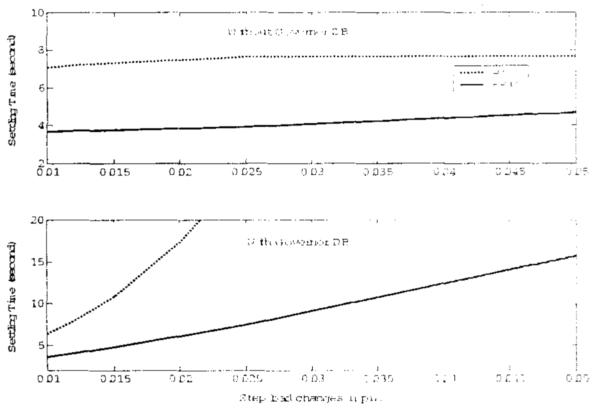


Fig. 9: A comparative settling times of FPIC and PI controller for an AGC in single area power system without and with Governor DB.

7. CONCLUSION

An intelligent automatic generation controller or load frequency controller has been developed to regulate the power output and system frequency. A simple fuzzy-PI controller is explained and investigated in this paper. From the above simulation results, it is clear that the proposed controller exhibits better performance to stable satisfactorily balance between frequency overshoot and transient oscillations with zero steady-state error. The various simulation results keenly show the superior of the proposed AGC controller in both cases with and without governor dead-band. The settling times (shown in Fig. 9) and 1st peak (given in Table 3) are also reduced to a great extent with the proposed mode of control.

References

[1] O.I. Elgerd, Electric Energy Systems Theory, McGraw-Hill Book Company, Newyork.

[2] H. Shayeghi, H.A. Shayanfar, A. Jalili, Multi-stage fuzzy PID power system automatic generation controller in deregulated environments, Energy Conversion and Management 47 (2006) 2829-2845.

[3] Q.P. Ha and H.Trinh, A variable structure-based controller with fuzzy tuning to load frequency control, International Journal of Power and Energy Systems 0(0) (2001) 1-5

[4] A. Demiroren, E. Yesil, Automatic generation control with fuzzy logic controllers in the power system including SMES units, Electrical Power and Energy Systems 26 (2004) 291-305.

[5] Y. L Karvanas and D. P. Papadopoulos, AGC for autonomous power system using combined intelligent techniques, Electric Power System Research 62 (2002) 225-239.

[6] Hadi Saadat, Power System Analysis, Tata McGraw-Hill Publishing Company Limited, NewDelhi.

[7] S.C. Tripathy, T.S. Bhatti, C.S. Jha, O.P. Malik, G.S. Hope, Sampled Data Automatic Generation Control Analysis with Reheat Steam Turbines and Governor Dead-Band Effects, IEEE Transactions on Power Apparatus and System PAS-103 (4) (1984).

[8] S. C, Tripathy, G.S. Hope, and O.P. Malik, Optimization Of Load-Frequency Control Parameters for Power Systems with reheat steam turbines and Governor deadband nonlinearity, IEE Proceedings 129 (Pt. C) (1) (1982).

[9] C. Concordia, L.K. Kirchmayer, and E.A. Szrnanski, Effect of speed governor dead-band on tie-line power and frequency control performance, AIEEE Trans. 76 (1957) 429-435.

[10] L.K. Kirchmayer,Economic control of interconnected systems, Wiley, 1959.

[11] D.D. Silzak, Nonlinear systems: the parameter analysis and design, Wiley, 1959.

[12] Ambalal V. Patel, Simplest Fuzzy PI controllers under various Defuzzification Methods, International Journal of Computational Cognition 3 (1) (2005) 21-34 (http://www.yangsky.us/ijcc/pdf/ijcc313.pdf).