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Fuzzy Based Integral Controller for an Automatic Generation Control in Multi-Area Power System

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Abstract – *In the present work, the intelligent load frequency controllers have been developed to regulate the power output and system frequency by controlling the speed of the generator with the help of fuel rack position control. This paper presents the implementation of fuzzy based integral controller (FIC) for controlling frequency and tie line power of in multi area power system. A comprehensive mathematical model of two area interconnected power system is developed. In the design of this controller, the conventional integral controller output is fuzzified by the fuzzy logic controller (FLC). The aim of the proposed controller is to restore the frequency in a very smooth way to its nominal value in the shortest possible time whenever there is any change in the load demand, etc. The action of this controller provides a satisfactory balance between frequency overshoot and transient oscillations with zero steady-state error. It is found that the proposed controller exhibits satisfactorily well dynamic performance and overcome all possible drawbacks associated with conventional integral controller (CIC).*

Keywords – Automatic generation control (AGC), conventional integral controller (CIC), fuzzy based integral controller (FIC).

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], [3]. Load Frequency Control (LFC), or automatic generation control, is a very important issue in power system operation and control for supplying sufficient and reliable electric power with good quality [2], [4], [5]. The goal of LFC is to reestablish primary frequency regulation capacity, return the frequency to its nominal value and minimize unscheduled tie line power flows between neighboring control areas [6]. Many investigations in the area of automatic generation control (AGC) of an interconnected power system have been reported in the past and a number of control strategies have been proposed to achieve improved performance [7]. In past decades, many research works have investigated AGC problem to improve its response in conventional power systems [8]. The conventional control strategy for the LFC problem is to take the integral of control error as the control signal. The conventional integral control (CIC) 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 [9]. Moreover, the transient settling time is relatively large [7]. 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 [10]. Consequently, the nonlinear nature of the load frequency control (LFC) problem makes it difficult to ensure stability for all operating points when an integral controller is used [11].

More recently, some modern ‘intelligent’ methods such as fuzzy logic control [12], adaptive control [13], fast acting artificial neural networks (ANN) [14] and genetic algorithms [15], have gained increasing interest for applications in the LFC problem. 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 [14].

The AGC based on fuzzy integral controller (FIC) 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 [16]. It provides an efficient way of coping with imperfect information, secondarily, it offers flexibility in decision making processes and thirdly, it provides an interesting man/machine interface by simplifying rule extraction from human experts and by allowing a simpler a posteriori interpretation of the system reasoning [17].

In this paper, a fuzzy integral controller (FIC) is designed and implemented to improve the transient behavior of the system. A typical two area interconnected power system is considered as a test network and comparative simulation results are presented and discussed.

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2. MODEL OF AGC IN TWO-AREAS POWER SYSTEM UNDER STUDY

In an interconnected 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. The first step in the analysis and design of a control system is mathematical modeling of the multi area power system. Proper assumptions and approximations are made to linearize the mathematical equations describing the system, and a transfer function model is obtained for the component [18].

Figure 1 shows a well known block diagram used for AGC of a typical two-area power system along with a CIC controller only [1], [18], [19]. The dynamic models in state-space variable form, obtained from the associated transfer function, is:

$$\dot{X} = AX + BU, \quad Y = CX \tag{1}$$

Where,

$X = [\Delta f_1\ \Delta f_2\ \Delta P_{12}\ \Delta P_{V1}\ \Delta P_{V2}\ \Delta P_{m1}\ \Delta P_{m2}\ \Delta P_{ref1}\ \Delta P_{ref2}]^T$; $U = [\Delta P_{L1}\ \Delta P_{L2}]^T$; $Y = [\Delta f_1\ \Delta f_2]^T$ 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 value [1], [18], [19].

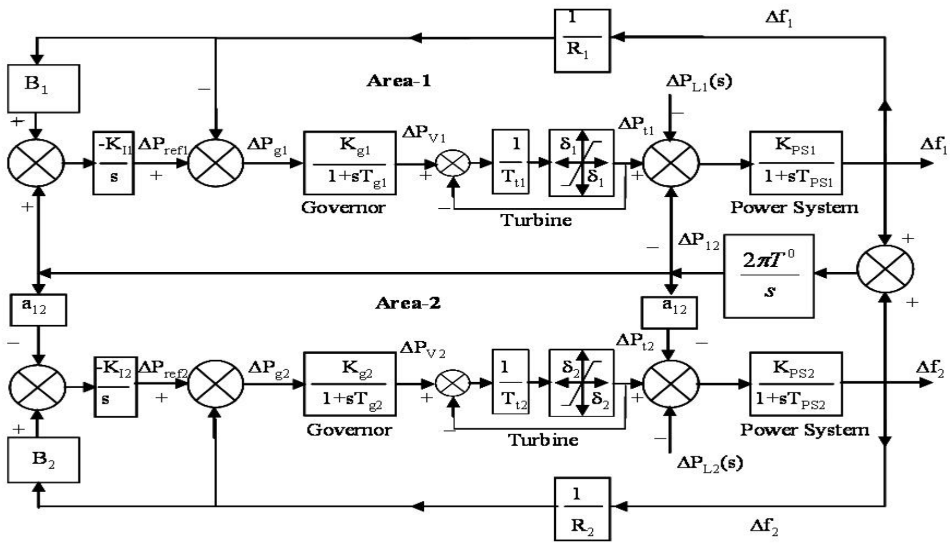

Fig. 1. A transfer function model for AGC of a typical two-area power system with considering GRC [1], [18], [19].

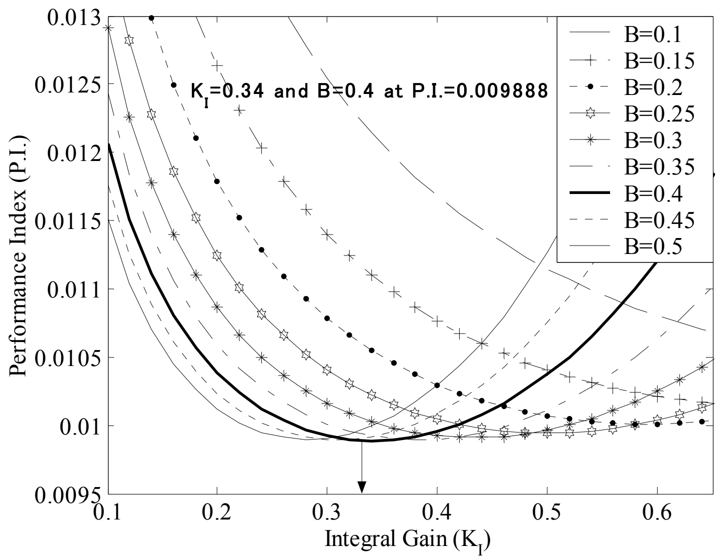

Fig. 2. The optimal integral controller gain, K_I and frequency bias factor, B.

In practical steam turbine systems, due to thermodynamic and mechanical constraints, there is a limit to the rate at which its output power (dP_t/dt) can be changed. This limit is referred to as generator rate constraint (GRC). A typical value of δ=0.0017 p.u. MW/s, applicable to most modern turbines, has been chosen for this study [19].

Determination of Optimal Value of the Integral Gain Value of K_I and Frequency Bias Factor, B

Dynamic performance of the AGC system would obviously depend on the value of frequency bias factors, $B_1 = B_2 = B$ and integral controller gain value, $K_{I1}=K_{I2}=K_I$. The optimal values of K_I and B are chosen, here, on the basis of a performance index (P.I.) [1], [18], [19] is given in Equation 2:

$$\text{P.I.} = \int_0^{40} \left(\Delta P_{tie}^2 + w_1 \Delta f_1^2 + w_2 \Delta f_2^2\right) dt \qquad (2)$$

where, w_1 and w_2 are the weight factors. The weight factors w_1 and w_2 both are chosen as 0.25 for the system under consideration. From Figure 2, it is observed that the value of Integral Controller gain, $K_I = 0.34$ and frequency bias factors, B=0.4 which occurs at P.I. = 0.0009888.

3. FUZZY BASED INTEGRAL CONTROLLER

Figure 3 shows a typical block diagram for fuzzy based integral controller (FIC) [20].

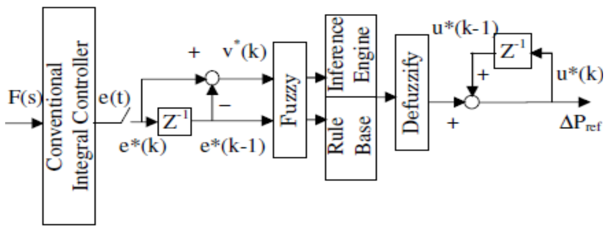

Fig. 3. A typical fuzzy based integral controller (FIC).

The discrete-time equivalent expression for conventional integral control (CIC) used in the chapter is given as:

$$e^*(k) = r^*(k) - y^*(k) \qquad (3)$$

$$\Delta e^*(k) \overset{\Delta}{=} e^*(k) - e^*(k-1). \qquad (4)$$

$$v^*(k) = \frac{[e^*(k) - e^*(k-1)]}{T_S} \qquad (5)$$

$$u^*(k) = K_I T_S \sum_{i=1}^{n} e^*(i) \qquad (6)$$

where, r*(k), y*(k) and e*(k) being the reference, output and error between the reference and the process output, respectively at k^{th} instant, T_S is the sampling time, u(k) is the control signal.

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

$$\Delta u^*(k) = u^*(k) - u^*(k-1) \qquad (7)$$

$$\Delta u^*(k) = K_I . e^*(k-1) \qquad (8)$$

where Δu*(k) is the incremental control effort at k^{th} instant and K_I is the integral gains of digital CIC controller, respectively.

4. DESIGN STEPS FOR FIC SCHEME

Automatic generation control of these closed loop control systems shown in Figure 1 means minimizing the area control errors (ACE_i). So that system frequency and tie-line interchanges are maintained at their scheduled values, respectively. The control error for each area consists of a linear combination of frequency and tie-line error [1], [18].

$$ACE_i = \sum_{j=1}^{n} \Delta P_{tie,i\,j} + B_i \Delta f_i \qquad (9)$$

where ACE_i is the area control error of i^{th} area, B_i is the frequency bias coefficient of i^{th} area, Δf_i the frequency error of i^{th} area, and $\Delta P_{tie,i}$ j is the tie-line interchange error between i^{th} area and j^{th} area. An overall satisfactory performance is achieved when the frequency bias factor of different areas are equal, i.e. $B_i = D_i + 1/R_i$. Thus, ACEs for a two area system are:

$$ACE_1 = \Delta P_{12} + B_1 \Delta f_1 \qquad (10)$$

$$ACE_2 = \Delta P_{21} + B_2 \Delta f_2 = a_{12} \Delta P_{12} + B_2 \Delta f_2$$

The CIC controller outputs will thus be of following the forms:

$$\Delta u_1 \overset{\Delta}{=} -K_{I1} \int (\Delta P_{12} + B_1 \Delta f_1) dt$$
$$\Delta \dot{u}_1 \overset{\Delta}{=} -K_{I1} (\Delta P_{12} + B_1 \Delta f_1) \qquad (11)$$

$$\Delta u_2 \overset{\Delta}{=} -K_{I2} \int (\Delta P_{12} + B_2 \Delta f_2) dt$$
$$\Delta \dot{u}_2 \overset{\Delta}{=} -K_{I2} (a_{12} \Delta P_{12} + B_2 \Delta f_2) \qquad (12)$$

where, $\Delta P_{12} = 2\pi f T_0 (\Delta f_1 - \Delta f_2)/s$ is the tie-line power, which flows from Area 1 to Area 2 and Δu is the CIC controllers output.

The same fuzzy based integral controller is used on both areas. In each area, the area control error supplied to the CIC controller and then output of the CIC controller fuzzified by the fuzzy logic controller (FLC) shown in Figure 3.

The FLC controller for each FIC has the two inputs which are defined as:

$$\text{Input1: error} = \Delta u \overset{\Delta}{=} -K_I \int (\Delta P_{12} + B \Delta f) dt = e_t \qquad (13)$$

Input 2: rate of change of error:

$$\Delta \dot{u} \overset{\Delta}{=} -K_1 (\Delta P_{12} + B \Delta f) = de_t / dt \qquad (14)$$

where, $\Delta f = f_{nom} - f_t$. 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 Figure 4.

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

$$\mu(e_t, c\dot{e}_t) = \min[\mu(e_t), \mu(de_t/dt)] \qquad (15)$$

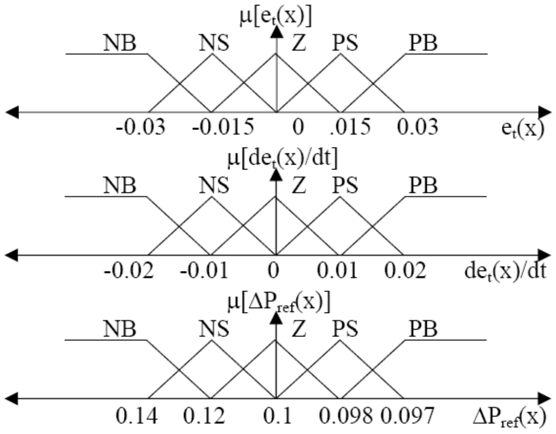

Fig. 4. Membership functions for the fuzzy variable of the proposed FIC.

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

$$\Delta P_{ref} = \sum_{j=1}^{n} \mu_j C_j \Big/ \sum_{j=1}^{n} \mu_j \qquad (16)$$

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

Table 1. Rule base for FIC controller.

e_t → / de_t/dt ↓	NB	NS	Z	PS	PB
NB	PB	PS	PS	PS	Z
NS	PS	PS	PS	Z	NS
Z	PS	PS	Z	NS	NS
PS	PS	Z	NS	NS	NB
PB	Z	NS	NS	NB	NB

5. SIMULATION RESULTS AND DISCUSSION

In order to demonstrate the beneficial damping effect of the proposed fuzzy based integral controller of automatic generation controller in a multi area power system, computer simulations results based on system non-linear differential equations are carried out for different load changes. The differential equations are solved by using the 4th order Range-Kutta method under MATLAB environment. The MATLAB software has been used in overall simulation work.

Case I. The step load is applied to only one area

In this case, FIC controller of the loaded area is active only to resotore the frequency to its nominal value and the output of the FIC controller for the unloaded area is same as the CIC controller output. Figure 5 shows the responses of the frequency deviations, power generation of both areas and Tie-line power deviation and generation rate constraints (GRC). From this figure, it is clearly depicted that the frequency devaition in both areas is comparatively 50% less oscillated than that of CIC controller and of reference [3]. The settling time is greatly reduced to the value 3.54s as compared to the CIC controller and of reference [3]. It is observed that the tie-line power flows from Area 2 to Area 1 in both cases. The typical value of the GRC is maintained to 0.0017 p.u. MW/s.

Case II. Same step load is applied on both areas

In this case, FIC controller of the both areas is active to restore the frequency to its nominal value separately. If the both areas have the same capacity and same step load changes, the FIC controller of each area adjusts their own load individually. Figure 6 depicts the simulation results for the same step load changes of ΔP_L=0.01p.u in both areas. It is clearly observed that the 1st peak of the frequency deviation in each area is reduced to 55% than that of CIC controller, 3rd peak is near about zero and 4th peak of each figure is fully diminished and the settling time is very small compared to the CIC controller (within 2.55s) and of references [3], [4]. Tie line power in this case must be zero because the both area have the same capacity and same load is applied on each area. The typical value of the GRC is maintained to 0.0017 p.u. MW/s.

Case III. Different step load is applied on both areas

In this case, both areas are loaded by the different loads, each area adjusts their own load separately. Lower loaded area shared the extra load of the higher loaded area. Figure 7 exhibits the system performances for the step load changes of ΔP_{L1}=0.02 and ΔP_{L2}=0.01 p.u., respectively. It is clear that the oscillation of the frequency deviation is decreased 50% than that of CIC controller and of references [3], [4]. The 3rd and 4th peaks of oscillations are completely diminished. Here, the settling time is very small compared to the CIC controller. The tie-line power flows from Area 2 to Area 1.

In all three cases, power generation of each area is equal to their corresponding step load changes and the generation rate constraints (GRC) of each area is used as need as possible to adjust their corresponding load.

Tables 2 and 3 show the comparison of performances between the FIC controller and CIC controller in multi area power system. These settling times are also better than that of fuzzy logic based LFC controller [3], [4].

Table 2. Time to reach 1st peak.

Load in one area(ΔP_{L1}=0.0 and ΔP_{L2}=0.01 p.u)		Same Load in both areas (ΔP_{L1}= ΔP_{L2}=0.01 p.u)		Different Load ΔP_{L1}=0.02; and ΔP_{L2}=0.01 p.u)	
FIC	CIC	FIC	CIC	FIC	CIC
-0.012	-0.021	-0.0150	-0.027	-0.018	-0.036
0.32s	0.59s	.35s	0.74s	0.38s	0.7s

Table 3. Setting times.

Step load change p.u.	Load in one area Only		Same load in both areas	
	FIC	CIC	FIC	CIC
0.01	3.54s	11.052s	2.55s	13.44s
0.012	3.57s	11.52s	2.87s	14.12s
0.015	3.71s	12.146s	3.21s	14.73s
0.02	3.6s	13.489s	3.43s	14.74s
0.025	3.62s	15.2s	3.725s	16.1s
0.05	4.65s	16.72s	3.84s	17.8s

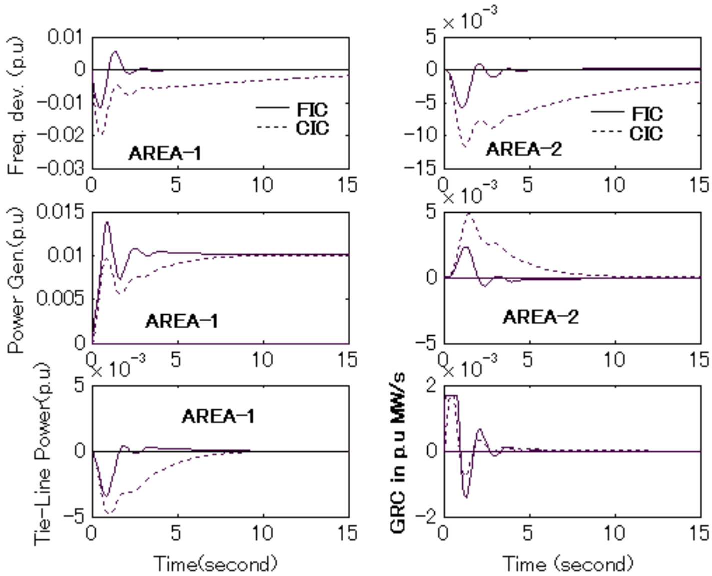

Fig. 5. Frequency deviation, power generation, tie-line power and generation rate constraints (GRC) for step load change ΔP_{L1}= 0.01 p.u in area 1 only.

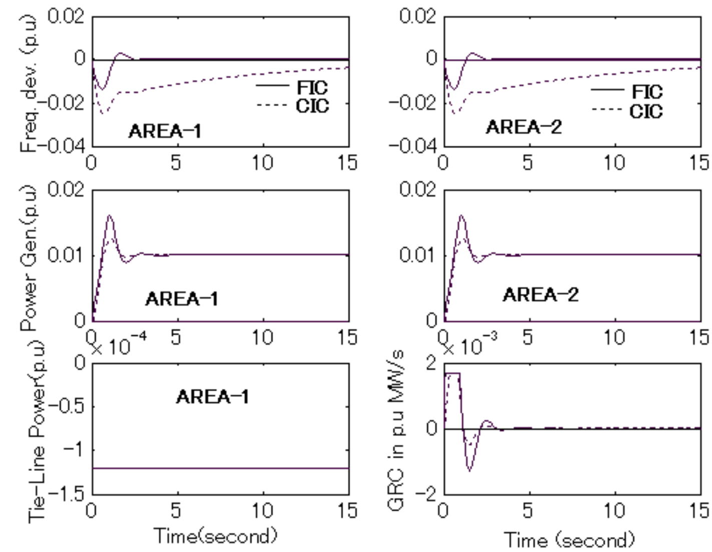

Fig. 6. Frequency deviation, power generation, tie-line power and generation rate constraints (GRC) for same step load change $\Delta P_{L1} = \Delta P_{L2} = \Delta P_L$= 0.01 p.u in both areas.

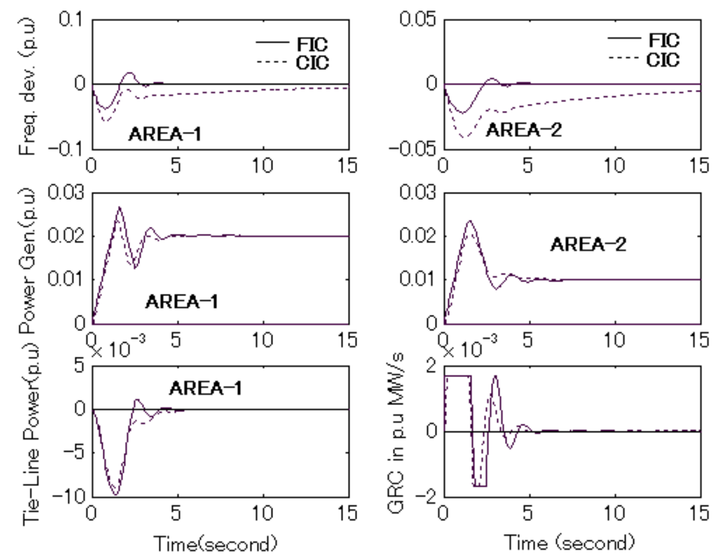

Fig. 7. Frequency deviation, power generation, tie-line power and generation rate constraints (GRC) for step load change ΔP_{L1} = 0.02 p.u and ΔP_{L2} = 0.01 p.u.

6. CONCLUSION

An intelligent load frequency controller has been developed to regulate the system frequency and tie-line power of multi area power system. The proposed FIC provides a satisfactory stability between frequency overshoot and transient oscillations with zero steady-state error. The various simulation results clearly indicate that the proposed scheme exhibit superior performance than that of CIC controller and of references [3], [4]. The settling time is reduced to a great extent with the proposed mode of control. The design procedure of the FIC controller may be applied in three area or more area power systems, possibly with simpler structure and with careful examination of its potential properties.

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