AUTOMATIC GENERATION CONTROL WITH FUZZY LOGIC CONTROLLER IN THE POWER SYSTEM INCLUDING THREE AREAS

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ABSTRACT

This study presents a method based on fuzzy logic controllers (FLCs) for automatic generation control (AGC) of power system including three areas having two steam turbines and one hydro turbine tied together through power lines. The results obtained by using FLCs proposed in this paper outperform than those of conventional controllers as settling time and overshoot as shown at simulation.

I. INTRODUCTION

The AGC problem, which is the major requirement in parallel operation of several interconnected systems, is one of very important subjects in power system studies. In this study, the power system with three areas connected through tie-lines are considered. The perturbation of frequencies at the areas and resulting tie-line power flows arise due to unpredictable load variations that cause mismatch between the generated and demanded powers. The objective of AGC is to minimize the transient deviations and to provide zero steady state errors of these variables in a very short time. In literature, for AGC, some control strategies based on classical control theory have been proposed [1-5].

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 FLC, which represents a model-free type of nonlinear control algorithms, could be a reasonable solution. Fuzzy PI-type controller has some advantages: (i) it provides an efficient way of coping with imperfect information, (ii) it offers flexibility in decision making processes, (iii) 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 [6]. FLCs are knowledge-based controllers usually derived from a knowledge acquisition process or automatically synthesized from self-organizing control architectures. These controllers typically define a nonlinear mapping from the system's state space to the control space. Thus each FLC can be visualized as a nonlinear control surface reflecting a process operator's or a product engineer's prior knowledge. Each control surface is represented in a Knowledge Base and executed by an interpreter [7].

In this paper, the power system with three areas having two steam turbines and one hydro turbine is considered in simulation study. In the study, the simulation is implemented by using MATLAB Simulink Program and MATLAB Fuzzy Logic Toolbox [8]. To damp out the oscillations due to instantaneous load perturbations as fast as possible, AGC including the FLC is used. The results obtained show that the controller improves effectively the damping of the oscillations after the load deviation in one of the areas in the interconnected system compared to conventional controllers.

On the other hand, a characteristic specification of this study is that the governors at all areas in power system have deadbands, which are important for speed control under small disturbances. The deadband affects the stability of the power system. It is known that governor deadband has destabilization effect on the transient response. Moreover, reheater effects and boiler effects are very important for the stability of the systems having steam turbine as known in the literature [1,9]. Therefore, the effects of boiler and reheater of each thermal area in the power system are considered in the study.

In the simulation, a step load increase in the first area of the power system is considered. For comparison, the considered power system is controlled by using:

i. Conventional proportional-integral (PI) controllers,
ii. Fuzzy PI-type controllers.

The results obtained show that the performance of fuzzy controller is better than conventional integral controller, as the main objective of the study.

II. MODELLING FOR AGC AT THE POWER SYSTEM WITH THREE AREAS

An interconnected power system is considered as being divided into control areas, which are connected by tie-lines. In each control area, all generators are assumed to form a coherent group. Some of the areas in the power system are considered having load perturbations having same magnitudes.

The considered power system is assumed to contain two reheat turbine type thermal units and a hydro unit as shown in Figure 1. The system data is given in Table 1.

In conventional system, turbine reference power of each area is tried to be set to its nominal value by an integral controller and the input of the integral controller of each area is $B_i\ \Delta f_i+\Delta P_i$ ($i=1,..,3$) called as area control error (ACE) of the area.

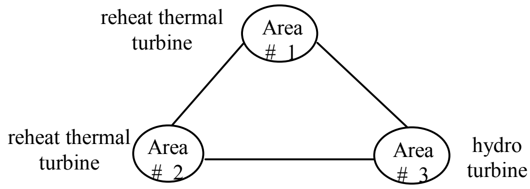


Figure 1 The power system with three areas

Each of two areas including steam turbines contains governor, reheater's stage of steam turbine and generation rate constraints. All of the governors have deadband effects that are important for speed control under small disturbances [1]. The reheater effect to the steam turbines is considered in the state space model equations.

Table 1 The power system data (2000MW area capacity)

$K_{P1,2}$	120	$T_{G1,2}$	0.2s.	T_1	48.7s.
$T_{P1,2}$	20s.	$K_{I1,2,3}$	0.001	T_2	0.513s.
$T_{s1,2}$	0.001s.	$R_{1,2,3}$	2.4	T_3	10s.
$K_{R1,2}$	0.333	$T_{E1,2,3}$	0.3s.	T_W	1s.
$T_{R1,2}$	10s.	ΔP_{D1}	0.01p.u.MW	a_{ij}	-1
T_{P3}	13s.	K_{P3}	80		

A describing function approach is used to linearize the governor deadband in terms of change and rate of change in the speed [1,5,9]. The governor deadband is defined, as the total magnitude of a sustained speed change within which there is no change in valve position. The non-linearity of hysteresis is expressed as y=F(z,dz/dt). For a basic assumption, the variable x is taken as a sinusoidal oscillation such as $z \approx A\sin\omega_0 t$, where A is the amplitude of oscillation, ω_0 is the frequency of oscillation and $\omega_0=2\pi f_0=\pi$ with f_0=0.5 Hertz. F(z,dz/dt) function can be evaluated as a Fourier series[1]. For a reasonable approximation, it is enough to consider the first three terms. As the blacklash non-linearity is symmetrical about the origin, then F_0 is equal to zero and

$$F(z, dz/dt) = N_1 x + \frac{N_2}{\omega_0} dz/dt \; DBz \tag{1}$$

where DB denotes the deadband [5,9]. For the analysis in this paper, backlash of approximately 0.5% is chosen[9]. As result, the fourier coefficients are obtained as N_1=0.8 and N_2=-0.2.

Boiler System

In this study, the effect of the boiler at each steam area in the power system is also considered as detailed configuration given by Figure 2 [9]. This includes the long-term dynamics of fuel and steam flow on boiler drum pressure. Representation for combustion controls is also incorporated. The model is basically for a drum type boiler, similar responses have been observed for once-through boilers and pressurized water reactors. The model can be used to study the responses of coal fired units with poorly tuned combustion controls and well tuned oil or gas fired units. In conventional steam units, changes in generation are initiated by turbine control valves and the boiler controls respond with necessary immediate control action upon sensing changes in steam flow and deviations in pressure [9]. As a result, the state space equations of the power system are written as following:

$$\dot{x} = Ax + Bu + G \tag{2}$$

where G is a vector containing non-linear terms. The state variables and input for the power system with three areas in the case of using conventional PI controller are

$x^T=[\Delta f_1, \Delta P_{R1}, \Delta P_{G1}, \Delta P_{ref1}, \Delta x_{E1}, \Delta f_2, \Delta P_{R2}, \Delta P_{G2}, \Delta P_{ref2}, \Delta x_{E2}, \Delta f_3, \Delta x_{E3}, \Delta P_{R3}, \Delta P_{G3}, \Delta P_{ref3}, \Delta P_{12}, \Delta P_{23}, \Delta P_{31}]$

$u^T=[\Delta P_{D1}, \Delta P_{D2}, \Delta P_{D3}]$

the parameters in equation above are given in Reference [10].

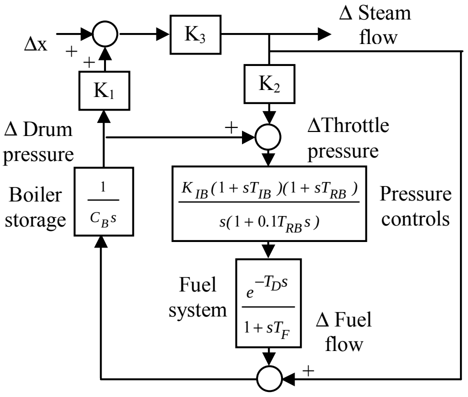


Figure2 The detailed configuration of boiler

Moreover, in order to project physical constraints, a generation rate limitation of 0.1 p.u. per minute (i.e. 0.0017 p.u. MW/sec.) for thermal areas and 4.5% per second for hydro unit are considered [5]. By considering the matters mentioned above, the state space equations are obtained in Laplace domain as given in Appendix.

III. FUZZY LOGIC CONTROLLERS

The AGC based on FLC 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 FLC, which represents a model-free type of nonlinear control algorithms, could be a reasonable solution. There are many possibilities to apply fuzzy logic to the control system. A fuzzy system knowledge base consists of fuzzy IF-THEN rules and membership functions characterizing the fuzzy sets [6]. The result of the inference process is an output represented by a fuzzy set, but the output of the fuzzy system should be a numeric value. The transformation of a fuzzy set into a numeric value is called defuzzification. In addition, input and output scaling factors are needed to modify the universe of discourse. Their role is to tune the fuzzy controller to obtain the desired dynamic properties of the process-controller closed loop [6].

In this paper, the inputs of the proposed Fuzzy controllers are area control error (ACE), and change rate in area control error (ΔACE) as shown in Figure3, which is indeed error (e) and the derivation of the error ($\dot{e}$) of the system, respectively. This gives us a fairly good indicator of the general tendency of the error.

According to the conventional automatic control theory, the performance of the PI controller is determined by its proportional parameter K_P and integral parameter K_I [11]. The proportional term provides control action equal to some multiple of the error, while the integral term forces the steady state error to zero. Whenever the steady-state error of the control system is eliminated, it can be imagined substituting the input ΔACE of the fuzzy controller with the integration of error. This will result in the fuzzy controller behaving like a parameter time-varying PI controller; thus the steady-state error is removed by the integration action. However, these methods will be hard to apply in practice because of the difficulty of constructing fuzzy control rules. Usually, fuzzy control rules are constructed by summarizing the manual control experiences of an operator. The operator intuitively regulates the executer to control the process by watching the error and the change rate of the error between output of the system and the set-point value given by the technical requirement. It is no practical way for the operator to observe the integration of the error of the system. Therefore it is impossible to explicitly abstract fuzzy control rules from the operator's experience. Hence, it is better to design a fuzzy controller that possesses the fine characteristics of the PI controller by using only ACE and ΔACE.

One way is to have an integrator serially connected to the output of the fuzzy controller, as shown in Fig. 3 [12,13]. The control input to the plant can be approximated by

$$u = \beta \int u_t dt \tag{3}$$

where β is the integral constant, or output scaling factor. Hence, the fuzzy controller becomes a parameter time-varying PI controller. The controller is called as PI–type fuzzy controller, and the fuzzy controller without the integrator as the PD–type fuzzy controller. In a PI–type fuzzy control system, the steady-state error is zero, but when the integral factor is small the response of the system is slow, and when it is too large there is a high overshoot and serious oscillation [13].

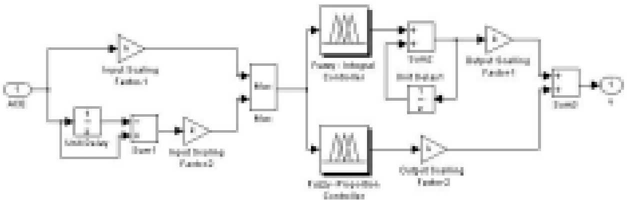


Figure3. The PI-type fuzzy controller

In this paper, a controller structure that simply connects the PD-type and PI-type fuzzy controller together in parallel is proposed. The fuzzy controller is shown in Figure 4 [13], where α is the weight on the PD-type fuzzy controller and β is that on the PI–type fuzzy controller. Whenever the value of α/β is large, it means that the derivative control is more effective than the integral control, and vice versa. From another point of view, the fuzzy controller behaves as a time-varying PID controller.

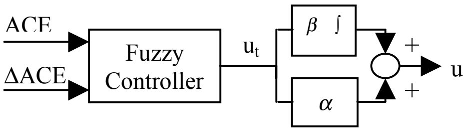


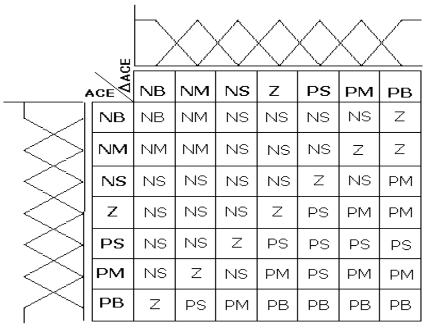
Figure 4. The proposed PI-type fuzzy controller

The type of the FLC obtained is called Mamdani-type which has fuzzy rules of the form

If ACE is A_i and ΔACE is B_i THEN u is C_i i=1,…, n.

Here, A_i, B_i, C_i, are the fuzzy sets. The triangle membership functions for each fuzzy linguistic values of the ACE and ΔACE are shown in Table 2 [8], in which NB, NM, NS, Z, PS, PM, and PB represent negative big, negative medium, negative small, zero, positive small, positive medium, and positive big, respectively.

Table 2. Lookup table of fuzzy rules



ACE \ ΔACE	NB	NM	NS	Z	PS	PM	PB
NB	NB	NM	NS	NS	NS	NS	Z
NM	NM	NM	NS	NS	NS	Z	Z
NS	NS	NS	NS	NS	Z	NS	PM
Z	NS	NS	NS	Z	PS	PM	PM
PS	NS	NS	Z	PS	PS	PS	PS
PM	NS	Z	NS	PM	PS	PM	PM
PB	Z	PS	PM	PB	PB	PB	PB

IV. SIMULATION RESULTS

In this study, the application of Fuzzy PI-type controller to AGC in the power system with three areas having two steam turbines and one hydro turbine tied together through power lines is investigated. The load perturbation having amplitude of 0.01 p.u. MW to the given area is applied and the frequency oscillations and tie-line power flows are investigated. The simulation incorporates detailed model for the boiler dynamics, steam reheat process and governor deadband non-linearity effects using the describing function approach and the limits of the rate of generating power belonging to each thermal unit area. The oil/gas-fired boiler used in thermal units of the power system considered is having the fastest response among boilers as known in literature. Governor deadband negative effect on settling time and on the amplitude of oscillation is known therefore governor effects are taken into account. Moreover, the physical boundaries such as generating limits at each area are taken into account. The conventional PI controllers and fuzzy logic PI-type controllers of Mamdani type are investigated as comparison due to load perturbation in each area at the power system.

In Figure 5 a to f, the deviations of frequencies of each area and the deviations of tie-line power flows for a step load perturbation at only first area are shown, respectively. In the figures, the results are given as compare with the cases of conventional PI controller and Fuzzy PI-type controller. The dashed lines represent the case of fuzzy PI controllers, and dotted lines represent the case of conventional controllers.

The aim of the study is to investigate the effects of Fuzzy PI-type controller on improving dynamic performance of the power system. The results obtained show that the performance of Fuzzy PI-type controller is better than conventional PI controller as the main objective of the study.

V. CONCLUSIONS

This study is an application of FLC to AGC in power system with three areas. In practice, power systems generally have more than two areas and each area has different properties from others. Because of this, in the study, the power system with three areas of which consisting of two thermal units and the other one consisting of a hydro unit is considered. In the simulation, detailed model incorporates the boiler dynamics, steam reheat process and governor deadband non-linearity effects using the describing function approach. Moreover, the physical boundaries such as generating limits are taken into account.

The nonlinear state space equations of the power system are used directly during the control of the system by FLC and by conventional proportional integral controller.

In the last ten years, fuzzy controllers are applied, successfully, to many industrial processes, which are mostly nonlinear. Since the power systems are also inherently nonlinear, nonlinear controllers are needed, so FLC s give a good solution. In this paper, a new FLC, called fuzzy PI-type, is applied to AGC in the power system having three areas. The design of the proposed FLC is very simple and effective. Since it is a model-free type of controller, it can be implemented to a power system. From the obtained results, it is shown that the performance of Fuzzy-PI controller outperforms than that of conventional PI controller at AGC in power system.

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APPENDIX

The state space equations of the power system is given as follows; for thermal unit in Laplace domain equations:

$$\Delta f_i(s)=\frac{K_{Pi}}{1+sT_{Pi}}\left[\Delta P_{Gi}(s)-\Delta P_{Di}(s)-\Delta P_i(s)\right] \tag{A-1}$$

$$\Delta P_{Ri}(s)=\frac{1}{1+sT_{Ti}}\Delta x_{Ei}(s) \tag{A-2}$$

$$\Delta P_{Gi}(s)=\frac{1+sK_{Ri}T_{Ri}}{T_{Ri}}\Delta P_{Ri}(s) \tag{A-3}$$

$$\Delta P_{refi}(s)=\frac{-K_{Ii}}{s}(B_i\,\Delta f_i(s)+\Delta P_i(s)) \tag{A-4}$$

$$\Delta x_{Ei}(s)=\frac{1}{1+sT_{Gi}}\left(\Delta P_{refi}(s)-\frac{1}{R_i}\Delta f_i(s)\right) \tag{A-5}$$

where subscript i represents each thermal area in power system (i=1,2). For hydro turbine state space equation in Laplace domain is given as below:

$$\Delta f_3(s)=\frac{K_{P3}}{1+sT_{P3}}[\,\Delta P_{G3}(s)-\Delta P_{D3}(s)-\Delta P_3(s)\,] \tag{A-6}$$

$$\Delta x_{E3}(s)=\frac{1}{1+sT_1}\left(\Delta P_{ref3}(s)-\frac{1}{R_3}\Delta f_3(s)\right) \tag{A-7}$$

$$\Delta P_{R3}(s)=\frac{1+sT_2}{1+sT_3}\Delta x_{E3}(s \tag{A-8}$$

$$\Delta P_{G3}(s)=\frac{1-sT_W}{1+0.5sT_W}\Delta P_{R3}(s \tag{A-9}$$

$$\Delta P_{ref3}(s)=\frac{-K_{I3}}{s}(B_3\,\Delta f_3(s)+\Delta P_3(s)) \tag{A-10}$$

The expression of deviations of tie-line power in the power system as follows:

$$\Delta P_{12}(s)=\frac{1}{s}(\,2\pi\,T_{12}\Delta f_1(s)-2\pi\,T_{12}\Delta f_2(s)) \tag{A-11}$$

$$\Delta P_{23}(s)=\frac{1}{s}\,(2\pi\,T_{23}\Delta f_2(s)-2\pi\,T_{23}\Delta f_3(s)) \tag{A-12}$$

$$\Delta P_{31}(s)=\frac{1}{s}(2\pi\,T_{31}\Delta f_3(s)-2\pi\,T_{31}\Delta f_1(s)) \tag{A-13}$$

The last state variables for each of these areas are ΔP_i (i=1,...,3) and the state space equation related to the variables are different for each area depending on the system configuration [10]. These are as following:

$$\Delta P_1(s) = \Delta P_{12}(s) + a_{31}\Delta P_{31}(s) \quad \text{(A-14)}$$

$$\Delta P_2(s) = a_{12}\Delta P_{12}(s) + \Delta P_{23}(s) \quad \text{(A-15)}$$

$$\Delta P_3(s) = a_{23}\Delta P_{23}(s) + \Delta P_{31}(s) \quad \text{(A-16)}$$

Parameters of thermal turbine and hydro turbine are given in [10, 14].

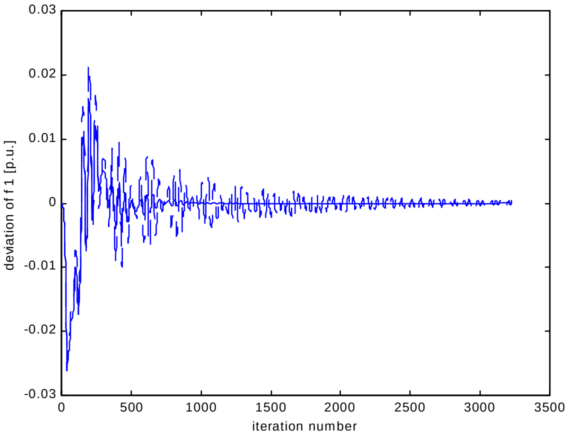

Figure 5a. The deviation of the frequency at area 1

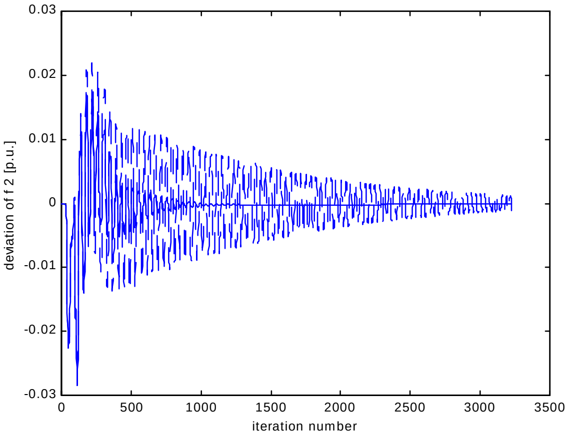

Figure 5b. The deviation of the frequency at area 2

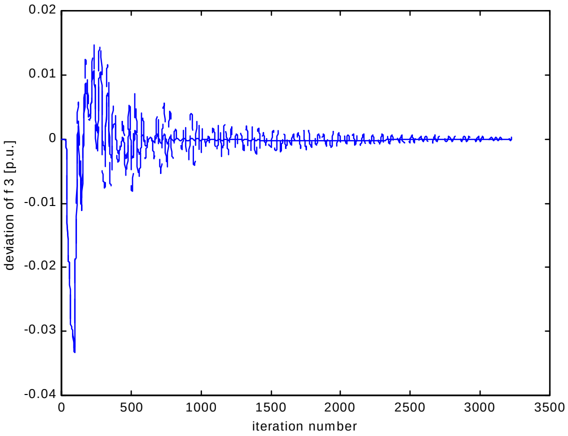

Figure 5c. The deviation of the frequency at area 3

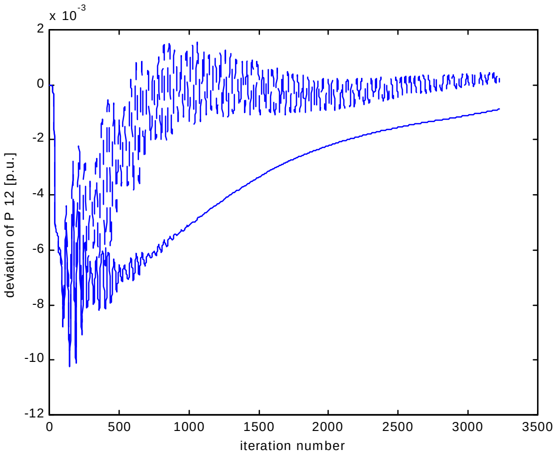

Figure 5d. The deviation of the tie-line power P_{12}

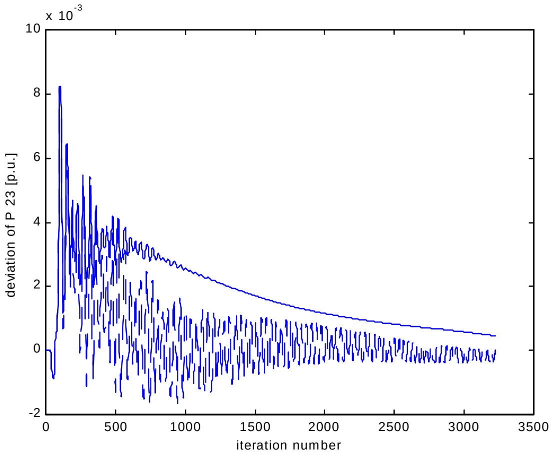

Figure 5e. The deviation of the tie-line power P_{23}

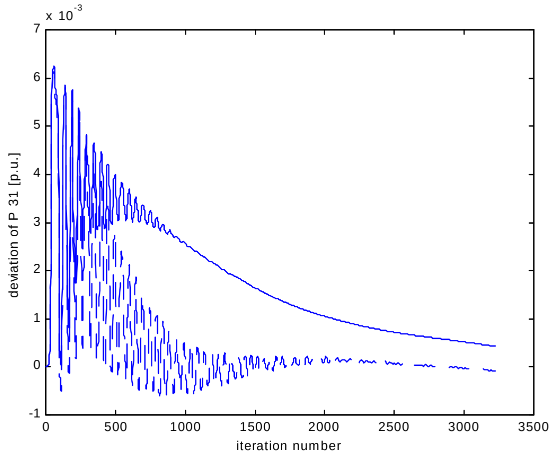

Figure 5f. The deviation of the tie-line power P_{31}