Chapter 21

A Two-Layered Load and Frequency Controller of a Power System

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Additional information is available at the end of the chapter

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1. Introduction

Automatic generation control (AGC) or called load frequency control (LFC) has gained a lot of interests in the past 30 decade (Benjamin &. Chan, 1982; Pan & Liaw, 1989; Kothari et al., 1989; Y. Wang et al., 1994; Indulkar & Raj, 1995; Karnavas & Papadopoulos, 2002; Moon et al., 2002; Sherbiny et al., 2003). LFC insures a sufficient and reliable supply of power with good quality. To ensure the quality of the power supply, it is necessary to deal with the control of the generator loads depending on the frequency with a proper LFC design. Therefore, the design of the controller is faced with nonlinear effects due to the physical components of the system, such as governor dead zone and generation rate constraints (GRC) and its complexity and the inherent characteristics of changing loads and parameters. Most actuators used in practice contain static (dead zone) or dynamic (backlash) non-smooth nonlinearities. These actuators are present in most mechanical and hydraulic systems such as servo valves. Their mathematical models are poorly known and limit the static and dynamic performance of feedback control system (Corradini & Orlando,2002). Conventional PI controller has been often used to achieve zero steady state frequency deviation. However, because of the load changing, the operating point of a power system may change very much during a daily cycle (Pan & Liaw, 1989). Therefore, a PI controller which is fixed and optimal when considering one operating point may no longer be suitable with various statuses. On the other hand, it is known that the classical LFC does not yield adequate control performance with consideration of the speed – governor non-smooth nonlinearities and GRC (Karnavas & Papadopoulos, 2002; Moon et al., 2002).

The problem of controlling systems with dead-zone nonlinearity has been addressed in the literature using various approaches some of which are dedicated to power systems. Reference (Tao & Kokotovic, 1994; X.-S. Wang et al., 2004) proposed adaptive schemes with and without dead zone inverse scheme, respectively, to track the error caused by the dead zone effect to zero. In the past decade, fuzzy logic controllers (FLC) have been developed successfully for analysis and control of nonlinear systems (Lee, 1990).

However, it has been sown by (Kim et al., 1994) that usual "Fuzzy PD" controller suffers from poor transient performance and a large steady state error when applied to systems with dead zones. On the other hand, when dealing with complex systems, the single-loop controller may not achieve the control performances and a multilayered controller turns out to be very helpful. The main advantage of the multilevel control lies in the freedom of the design of each layer (Yeh & Li, 2003; Oh & Park, 1998). The layers are designed to target particular objectives, so that design is simpler and performance improved. Motivated by the success of FLC, (Koo, 2001; Rubai, 1991) proposed new adaptive fuzzy controllers with online gain – tuning algorithm.

However, lots of computations are needed to calculate the adaptive control law with and without fuzzy system. To simplify the controller design (Kim et al., 1994) proposed a Two-layered fuzzy logic controller in which a fuzzy pre-compensator and a "fuzzy PD" controller were introduced to control plants with dead zones. Stimulated by ((Kim et al., 1994; L. X. Wang, 1997) designed a 2 layered fuzzy LFC (FLC-FLC) with the dead zone and GRC effects. Reference (Rubai, 1991) proposed a 2 layers fuzzy controller for the transient stability enhancement of the electric power system.

Based on the alternative choices proposed by (L. X. Wang, 1997) and the previous works (Kim et al., 1994; Sherbiny et al., 2003; Rubai, 1991], in this paper we study the case of a two-layer control architecture (FLC-CC) where the pre-compensator layer is constructed from fuzzy systems as a control supervisor and the other layer from the conventional method. In addition, we demonstrate that the proposed scheme exhibits a good transient and steady state performance, and is robust to load variations and system nonlinearities.

This paper is organized as follows. In section 2 we briefly introduce the systems investigated. Section 3 describes the idea underlying the approach and the design procedure of the proposed controller. The simulation plots that illustrate the behaviour of our scheme, taking into account parameters variations, GRC and speed governor dead zone are provided in section 4. Finally, conclusions based on extensive simulation results, recommendations and further research are drawn in section V.

2. Plant model

Power systems can be modeled by their power balance equations, linearized around the operating point. Since power systems are only exposed to small changes in load during their normal operation, a linear model can be used to design LFC. We consider the same single–area non reheat power system model as shown in Fig. 1. The investigated system consists of a speed–governor, a turbine that produces mechanical power, P_g, and the rotating mass (or power system). In steady state, P_g is balanced by the electrical power output, P_e, of the generator. Any imbalance between P_g and P_e produces accelerating power and thereby creates an incremental change in frequency, Δf. All parameters are given Appendix A.

The investigated model consists of a tandem-compound single non reheat turbine. The state space model can be expressed as following:

$$\dot{x}(t) = Ax(t) + BU(t) + F\Delta P_L \tag{1}$$

$$y(t) = Cx(t) \tag{2}$$

where:

$$A = \begin{bmatrix} -1/T_p & K_p/T_p & 0 & 0 \\ 0 & -1/T_t & 1/T_t & 0 \\ -1/RT_g & 0 & -1/T_g & -1/T_g \\ K_i & 0 & 0 & 0 \end{bmatrix} \tag{3}$$

$$B = \begin{bmatrix} 0 & 0 & 1/T_g & 0 \end{bmatrix}^T \tag{4}$$

$$F = \begin{bmatrix} -K_p/T_p & 0 & 0 & 0 \end{bmatrix}^T \tag{5}$$

$$C = [1 \ \ 0 \ \ 0 \ \ 0] \tag{6}$$

The time constant, T_g, in the governor model is quite small and often it is neglected, which means that the governor is assumed to act very fast compared to the change in speed or frequency. This leads to a second order dynamic power system model. But for accuracy and comparison purposes, T_g is considered.

In linear control system theory, it is required that a state feedback controller:

$$\Delta P_C = -Kx(t) \tag{7}$$

Hence, the closed loop eigenvalues become insensitive to variations of the system parameters.

2.1. Model 1: Single-area non reheat power system

Consider the same isolated non reheat power system model reported in (Benjamin &. Chan, 1982; Pan & Liaw, 1989; Y. Wang et al., 1994) as shown in Figure 1, with the system parameters given in appendix A.

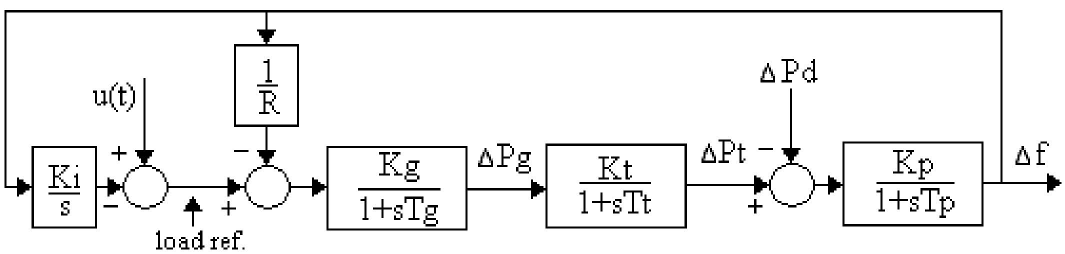

Figure 1. Block diagram of a isolated non reheat power system with supplementary control

Where u(t) denotes the existence of the proportional gain K_P, whereas its absence leads to an integral controller. The above described model has a tandem-compound single non reheat turbine and does not consider the speed-governor dead zone and GRC.

2.2. Model 2: two-areas reheat hydrothermal power system

The linearized mathematical model – 2 (see Fig.2), comprises an interconnection of two areas: single stages reheat thermal system (area 1) and a hydro system (area 2). The system parameters are given in appendix B. Figure 2 shows the small perturbation transfer function model of the hydro thermal system (Sherbiny et al., 2003). The speed governor dead zone and the GRC effects are also included in the model.

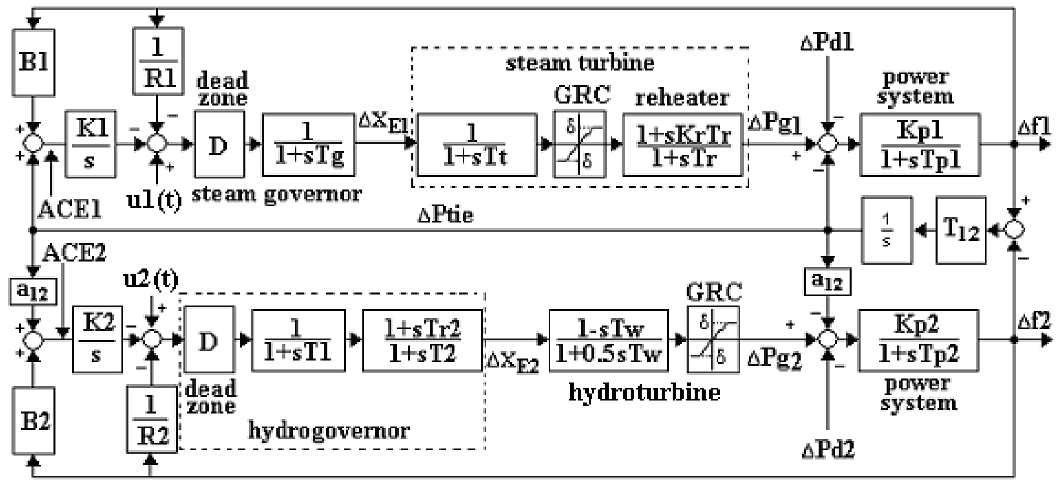

Figure 2. Bloc diagram of two-area reheat hydrothermal system with nonlinearities

3. Design of two layered controller for the system investigated

Considering the system shown in Figures 1, let P(s) represent the plant and D the speed governor actuator with dead zone (not present in Fig. 1). Recall that the supplementary PI control law can be written as following:

$$C_C[e(k), \int e(k)] = K_p e(k) + K_i \int e(k) \tag{8}$$

And in the case of "Fuzzy PD" controller, neglecting the scale factors, we get

$$C_F[e(k), \Delta e(k)] = F[e(k), \Delta e(k)] \tag{9}$$

C_C is a linear function of the error e(k) between the system output y_P(frequency deviation Δf) and the reference input Y_m (load reference ΔP_c) and the integral of the error whereas C_F is a function of the error and the change of error. From the above, we get

$$e(k) = y_m(k) - y_P(k) \quad \text{or} \quad y_P(k) = y_m(k) - e(k) \tag{10}$$

Let us assume that the supplementary control of the system is ensured by a "fuzzy PD" controller of the same type as (Indulkar & Raj, 1995; Karnavas & Papadopoulos, 2002).

3.1. Case 1: No actuator with dead zone

The plant output in this case can be written as

$$y_P(k) = P(s)\ \ F[e(k), \Delta e(k)] \tag{11}$$

Let $y_m(k) = y_m$. For steady state $\Delta e(k) = 0$ since the system is supposed to have reached the stabilizing time. Therefore, C_F becomes a function of e(k) alone and (11) can be written as following:

$$y_P(k) = K_s\ F[e_{ss}\ , 0] = y_m - e_{ss} \tag{12}$$

where K_s is the system static gain and is given by $K_s = \lim_{s\to 0} P(s)$

By assuming that C_F is well tuned and that the load reference deviation $y_m = \Delta P_c = 0$, (12) becomes:

$$K_s\ F[e_{ss}\ , 0] = -\ e_{ss} \tag{13}$$

Taking into account the feedback negative input sign into the controller (see Fig. 1), it can be verified from the description of Fuzzy PD controller (Indulkar & Raj, 1995; Karnavas & Papadopoulos, 2002). that the law F(. , 0) is an increasing odd function that can satisfy the following condition f(x) = -f(-x), with f(x) = F(. , 0). Therefore, it is clear that the solution to (13) is $e_{ss} = 0$, i.e., the steady state error of the system output is zero, as expected.

3.2. Case 2: Speed governor dead zone is present

The dead zone nonlinearity can be denoted as an operator is written as following:

$$u(k) = D(v(k)) \tag{14}$$

with v(k) as input and u(k) as output. The operator D(v(k)) has been described in detail by (Corradini & Orlando,2002; Tao & Kokotovic, 1994; X.-S. Wang et al., 2004; Oh & Park, 1998; Koo, 2001).The parameters of D(v(k)) are specified by the width 2d of the dead zone and the slop m of the response outside the dead zone. In this case, equation (12) can be written as :

$$y_P(k) = K_s D(v(k))\ \ F[e(k), 0] = y_m - e(k) \tag{15}$$

The solution to the equation (15) results in the steady state error as follow:

$$K_s D(v(k))\ \ F[e_{ss}\ , 0] - y_m = -\ e_{ss} \tag{16}$$

From (13) and (16) it can be seen that the steady state error e_{ss} in (16) is no longer zero. This is due to the presence of the dead zone in the speed governor actuator.

It has been demonstrated by (Yeh & Li, 2003) that the steady state error due to the dead zone in the actuator can be eliminated by adding some other constant η to the reference input y_m. We deliberately avoided using explicit knowledge of the value D(v(k)) because its parameters are poorly known or uncertain. Therefore, (16) becomes:

$$K_s D(v(k)) \; F[e + \eta \;, 0] - y_m = \; - e \tag{17}$$

Since PI controller is still the most used controller in power system (Pan & Liaw, 1989; Sherbiny et al., 2003) in our approach we use fuzzy logic rules to determine the appropriate value of η to be added to y_m. In this case, FLC plays the rule of a pre-compensator (supervisor) ensuring that the appropriate value of η is added to e(k) in order to eliminate the steady state error due to the dead zone. The conventional controller, called the stabilizer, present in the system, ensures the stabilization of the system.

The price to pay for changing the existing conventional controller into a FLC, which is proposed by (Sherbiny et al., 2003), would be in the computation. FLC is driven by a set of control rules rather than by two constant proportional and integral gains. As we shall see, the proposed scheme exhibits good transient and steady state behaviour. The proposed control scheme is depicted in Fig. 3 where C_1 is a FLC and C_2 a conventional controller. The feed-forward gain K_1 is normally set to the reciprocal of the K_s and constitutes an additional design parameter.

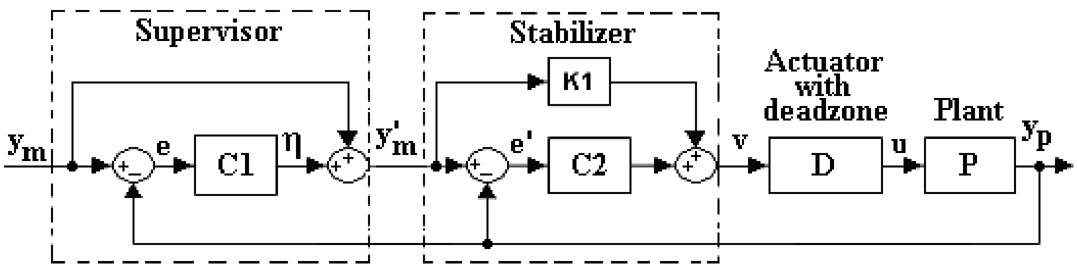

Figure 3. Proposed control structure

4. Design of the supervisor controller

As previously discussed, the first layer of the proposed control structure consists of the fuzzy logic based pre-compensator. The FLC law is based on standard fuzzy logic rules. It is well known that FLC consists of 3 stages, namely fuzzification, control rules inference engine and defuzzification. The reader is refereed to (Lee, 1990; L. X. Wang, 1997) for details on FLC. For LFC the process operator is assumed to respond to error e and change of error Δe (Indulkar & Raj, 1995); defined in (9). Considering the scale factors, (9) becomes as

$$C_F[e(k), \Delta e(k)] = F[n_e \, e(k), n_{\Delta e} \, \Delta e(k)] \tag{18}$$

where n_e and $n_{\Delta e}$ are the error and change of error scale factors respectively.

A label set corresponding to the linguistic variables control input e(k) and $\Delta e(k)$ with a sampling time of 0.1 sec is as follows: L(e, Δe) = {NB, NM, ZE,PM, PB} where, NB - Negative Big, NM - Negative Medium, ZE – Zero, PM - Positive Medium and PB - Positive Big. The membership functions (MFs) for the control input variables are shown in Fig. 4. The universe of discourse of each control variable is normalised from -1 to 1. The proposed control structure uses the center of gravity defuzzification method to determine the output control as following:

$$C_F[e(k), \Delta e(k)] = n_\eta \frac{\sum_i^m w_i y_i}{\sum_i^m y_i} \tag{19}$$

Where n_η is the output control gain, w_i is the grade of the ith output MF, y_i is the output label for the value contributed by the ith MF, and m is the number of contributions from the rules. The fuzzy output variable is determined by same MFs shown in Fig. 4 and labelled as following L(η) = {NB, NM, ZE, PM, PB}

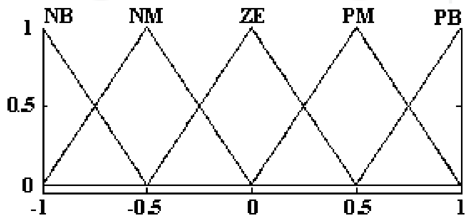

Figure 4. Membership functions of control input/output variables

The associated fuzzy matrices used in this work are given in table 1.

		e(k)				
		NB	NM	ZE	PM	PB
Δe(k)	NB	NB	NB	NB	NM	PM
	NM	NB	NB	NM	ZE	PM
	ZE	NB	NM	ZE	PM	PB
	PM	NM	ZE	PM	PB	PB
	PB	NM	PM	PB	PB	PB

Table 1. Fuzzy logic rules for pre-compensator C1

The performance of the FLC is affected by scaling factors of the inputs/output variables, MFs and the control rules. The selection of the optimum values of these factors is necessary in order to achieve satisfactory response [6]. But for the control system shown in Fig. 3, we can design the FLC without considering stability and use the stabilizer layer to deal with stability related problems.

5. Second layer: Stabilizer

The stabilizing layer consists of a conventional controller which is described in (8) and its design procedure is detailed in (Karnavas & Papadopoulos, 2002). The input to the present layer is the y'_m as shown in Fig. 3.

6. Simulation results

The power systems under investigation are simulated and subjected to different load disturbances in order to validate the effectiveness of the proposed scheme. The nonlinear effects, such as GRC and speed governor dead-zone, are also included in the simulations. The proposed controller (FLC-CC) will be evaluated qualitatively and quantitatively with

A single layer "PD FLC" (FLC) proposed in the first part of the work of (Karnavas & Papadopoulos, 2002) and a single layer conventional control (CC). The reader is referred to (Sherbiny et al., 2003) in order to compare our controller responses with the two-layered fuzzy controller proposed by (Sherbiny et al., 2003). The parameters of our controller for the two investigated models are given in table 2.

		n_e	$n_{\Delta e}$	n_η	K_p	K_i
Model 1		0.25	10.0	0.14	0.425	0.212
Model 2	area 1	10.0	20.0	0.15	4.00	6.00
	area 2	10.0	10.0	0.05	30.0	20.0

Table 2. Proposed controller parameters

6.1. Model 1 (Appendix A)

A step load perturbation of 10% (ΔP_d = 0.1 p.u.) of the nominal loading is considered. Fig 5 shows the simulation results of the frequency deviation Δf response to the step load change. The responses, obtained by the PD Fuzzy and the conventional controller (Karnavas & Papadopoulos, 2002) are also shown for comparison purpose.

Assume that the parameters R, Tg, Tt, Tp, Kp are subjected to a simultaneous changes of +30% from their nominal values. The frequency deviation response of the system is plotted in Fig. 6.

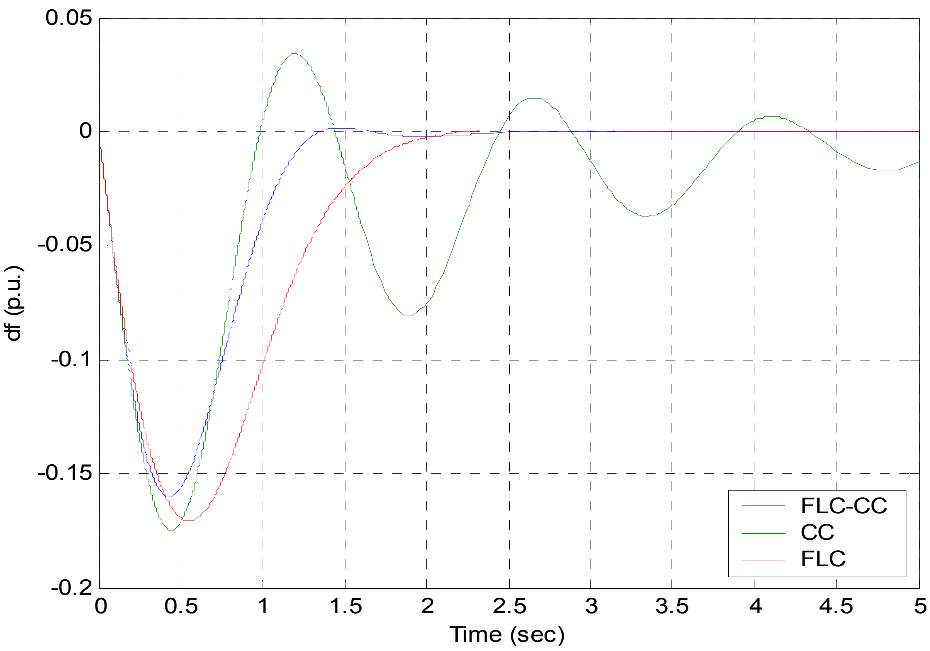

Figure 5. Frequency deviation for a load change of 0.1 p.u.

When GRC is applied to the system, its dynamic responses experience longer transient setting time t_s and larger overshoots OS compare to cases without the GRC. GRC of 3% p.u. MW/min and 10% p.u. MW/min are usually applied to reheat and non reheat turbines, respectively. In addition to GRC, the dead zone effect is also added to the system investigated. A dead zone width of 0.05 p.u. is considered. GRC and dead zone are taken into account by adding limiters to the turbines and an actuator to the speed governor input, respectively. Fig. 7 plots the responses of the system under nonlinear effects and a step load perturbation ΔP_d = 0.05 p.u.

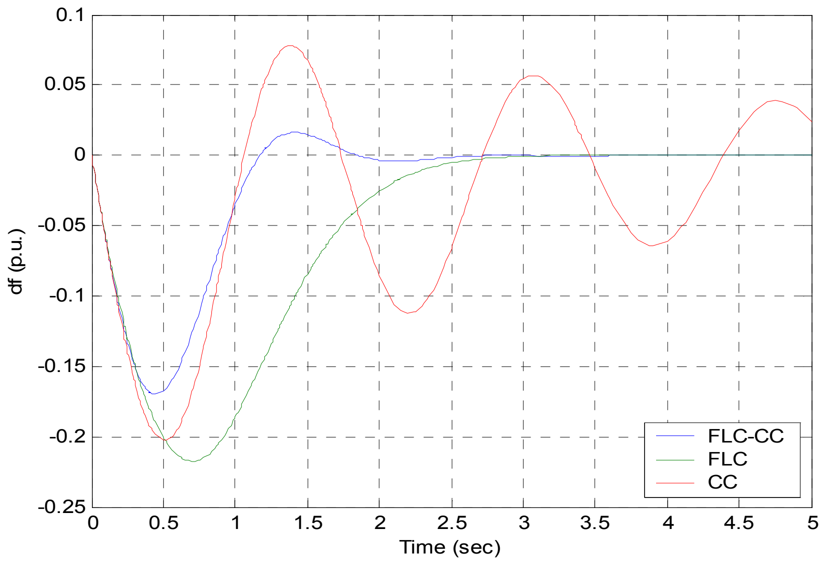

Figure 6. Frequency deviation at parameter changes of +30%

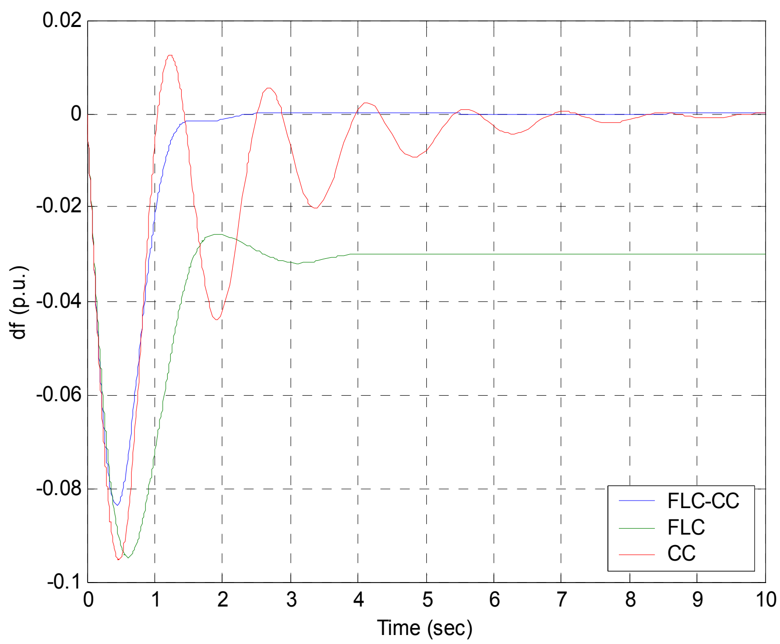

Figure 7. Frequency deviation due to ΔP_d = 0.05 p.u with nonlinear effects

From Figs. 5-7 it can be observed that the proposed controller acts as fast as the FLC-FLC controller with less oscillatory, less undershoot and setting time. In addition the proposed scheme is also robust to load and parameters changes with and without nonlinearities. Fig. 7 shows the system steady state error for the PD FLC as previously predicted.

6.2. Model 2: Appendix (B)

Fig 8-10 show the simulation results of the frequency deviations and the tie line power responses of the two area power system due to a step load perturbation $\Delta P_d = 0.05$ p.u. without non-linear effects. The responses obtained by the conventional controller (CC) are also shown for comparison purpose.

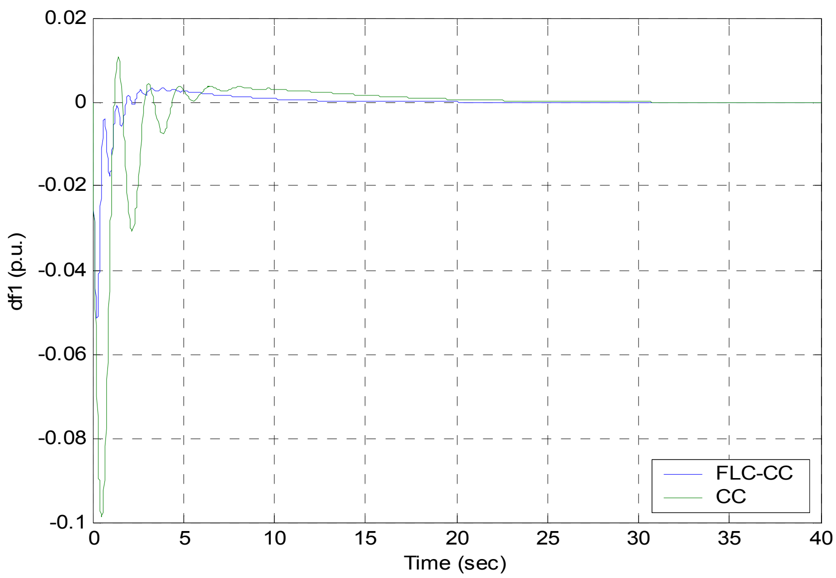

Figure 8. Frequency deviation of area 1 due to $\Delta P_{d1} = 0.05$ p.u.

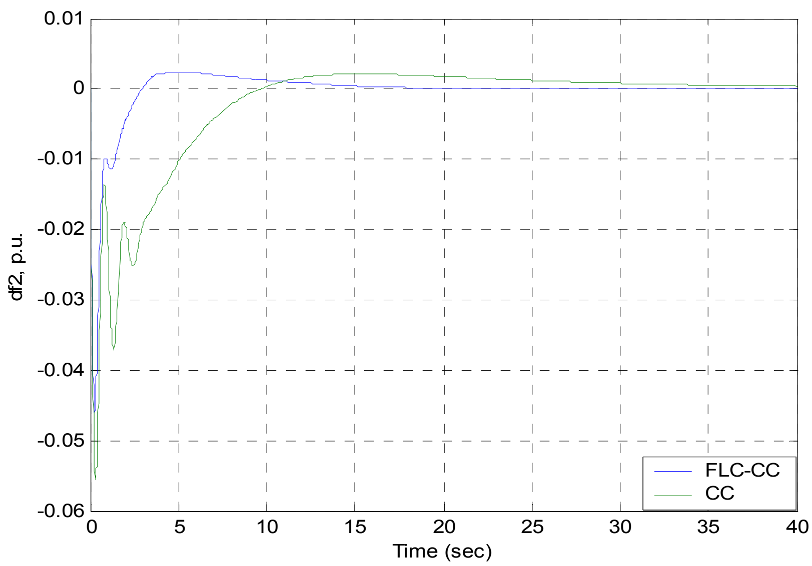

Figure 9. Frequency deviation of area 2 due to $\Delta P_{d2} = 0.05$ p.u

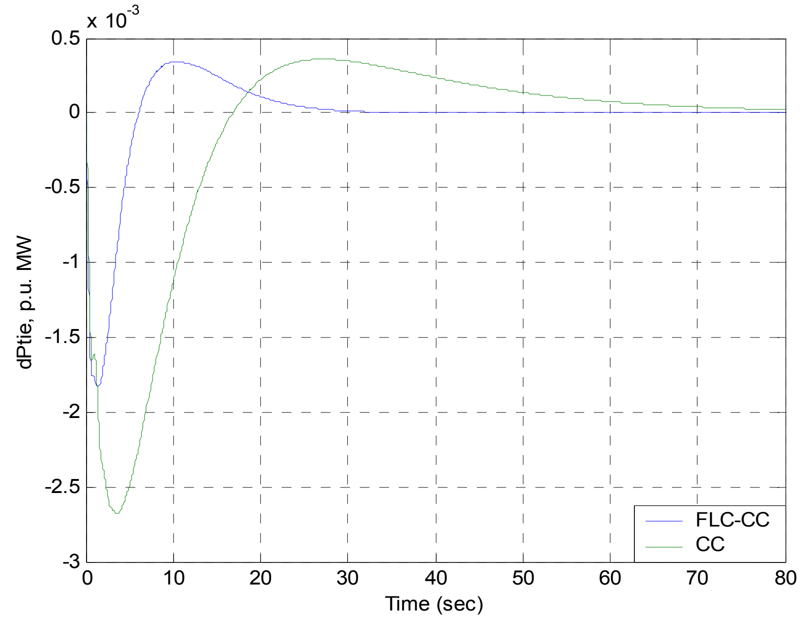

Figure 10. Tie line power deviation response due to ΔP_{d2}

It can be observed from the results obtained in Figs 8-10 that the proposed controller exhibits less oscillations and setting time compare to the conventional controller. Our controller responses are faster with smaller overshoot than the FLC-FLC controller. The reader is referred to (Sherbiny et al., 2003) for comparison.

Now assume that a dead zone width of 0.5 p.u. and GRC effects are considered in both area 1 and 2 simultaneously. Figs 11-13 plot the responses of the system under nonlinear effects.

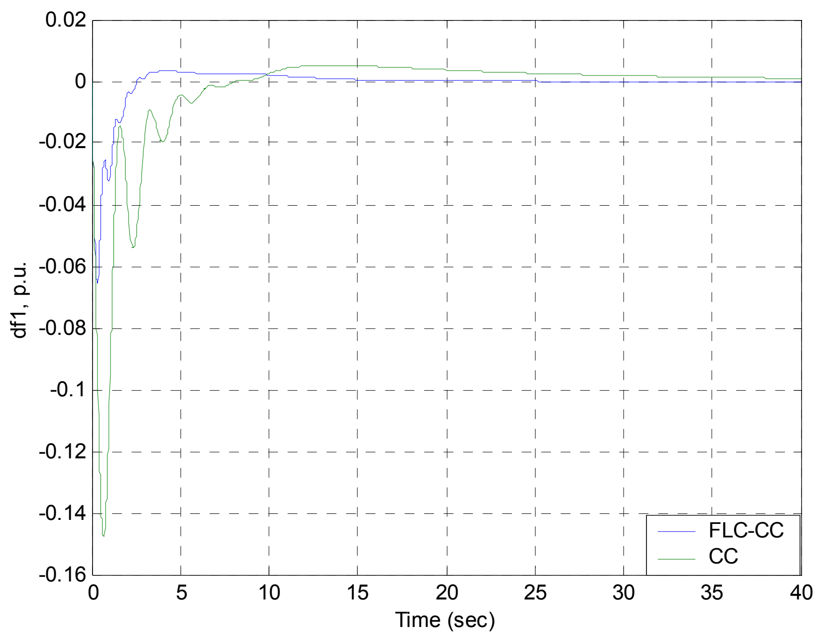

Figure 11. Frequency deviation of area 1 due to ΔP_{d1} = 0.05 p.u. with nonlinear effects

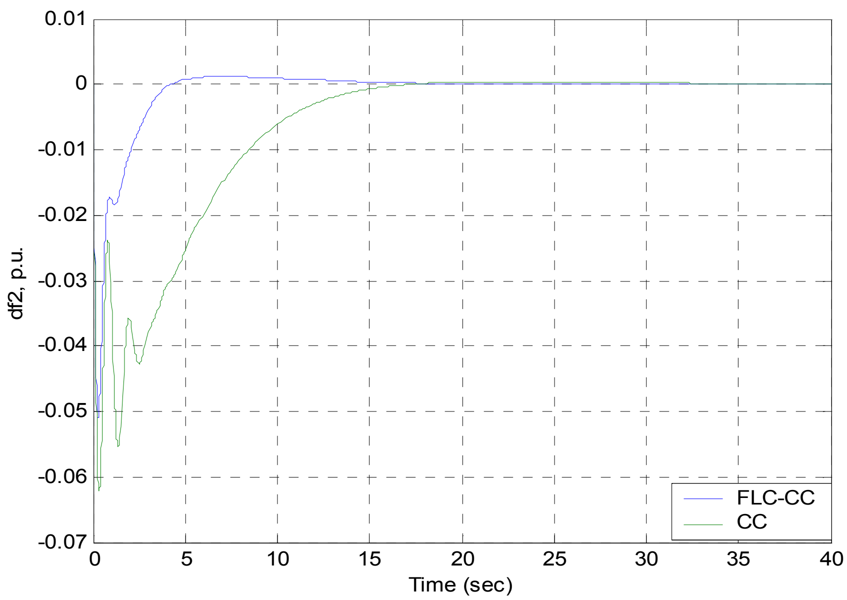

Figure 12. Frequency deviation of area 2 due to $\Delta P_{d2} = 0.05$ p.u. with nonlinear effects

Figures 11-13 demonstrate the robustness of the proposed controller under a large dead zone width and GRC. In addition, it has been possible to reduce the steady state error in the tie line power flow deviations (Fig 10, 13) using the proposed controller while it has been difficult with a single layered FLC proposed by (Indulkar & Raj, 1995).

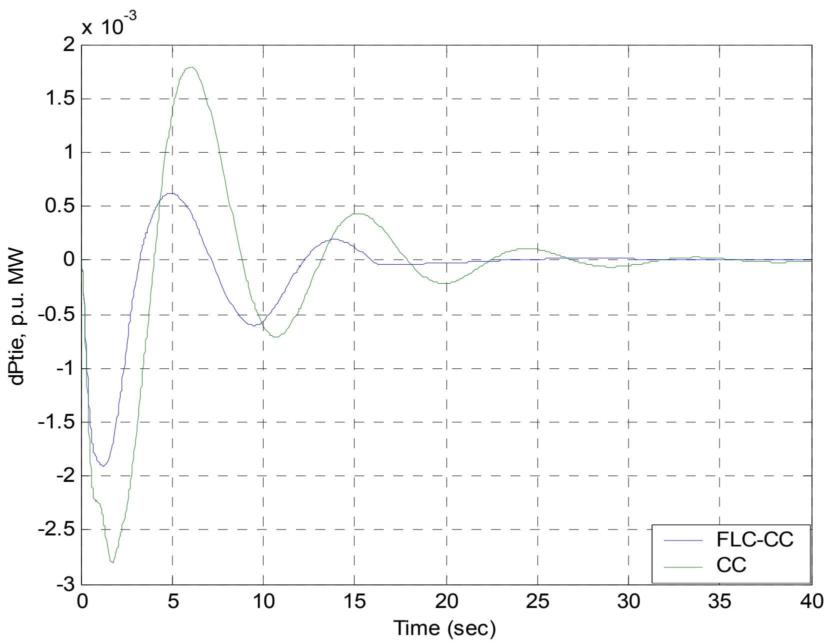

Figure 13. Tie line power deviation response due to $\Delta P_{d2} = 0.05$ p.u.

The performance Evaluation of The proposed controller (FLC-CC) is given by table 3.

		t_s [sec]		OS [p.u.] $\cdot 10^{-3}$		US [p.u.] $\cdot 10^{-3}$	
		w/NE	NE	w/NE	NE	w/NE	NE
ΔP_{tie} (Δf_1)	FLC-CC	10	17	0	0	1.2	3
	FLC-FLC	25	25	2.5	2.5	3.5	3.7
Δf_1	FLC-CC	5	5	0	0.1	45	52
	FLC-FLC	30	32	4.0	5	17	18
Δf_2	FLC-CC	12	10	0	0.1	45	45
	FLC-FLC	30	30	4	4	20	20

Table 3. Performance Evaluation Of The Proposed Controller (FLC-CC)

7. Conclusion

In this paper a two layered controller with a fuzzy pre-compensator is used to damp the power system frequencies and tie line power error oscillation and track their errors to zero. The price to pay for changing a conventional controller into a FLC in order to obtain a two layered controller, where both layers are FLC, would be in the computation. FLC is driven by a set of control rules rather than by two constant proportional and/or integral gains. In our approach, simple tuning of the conventional controller parameters enables the easy and cheap implementation of the proposed controller. Extensive simulations for a single area and an interconnected systems with no reheat, reheat and hydro turbines, taking into account a number of practical aspects such as the loads and parameters disturbances and the nonlinear effects, have verified the validity of our scheme over the conventional controller. Therefore, the proposed controller should be preferred. Further research is based on finding the optimum tuning method for the conventional controller parameters.

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Appendix A

Nominal Parameters Of A Typical Single-Area Nonreheat Power System (Model – 1):

T_p	- Electric system time constant	=	20,0 [s]
K_p	- Electric system static gain	=	120 [Hz $p.u.MW^{-1}$]
T_t	- Turbine time constant	=	0.30 [s]
T_g	- Governor time constant	=	0.08 [s]
R	- Speed regulation due to governor action	=	2.40 [Hz $p.u.MW^{-1}$]
ΔP_d	- load demand change		[p.u. MW]
ΔP_g	- incremental generation change		[p.u. MW]
ΔX_E	- incremental governor valve position change		
Ki	- integral control gain		
s	- the Laplace operator		

* Corresponding Author

Appendix B

Nominal Parameters Of ATwo-Area Reheat Hydrothermal Power System (Model – 2) :

i	- subscript referring to area	=	1,2
ΔX_{Ei}	- incremental governor valve position change		
K_i	- integral control gain		
T_{12}	- synchronising coefficient		
ΔP_{tie}	- incremental change in tie-line power		[p.u. MW]
ΔP_{gi}	- incremental generation change		[p.u. MW]
ΔP_{di}	- load demand change		[p.u. MW]
P_{ri}	- rated area power		[p.u. MW]
T_r	- reheat time constant	=	10.0 [s]
T_g	- governor time constant	=	0.08 [s]
T_t	- turbine time constant	=	0.30 [s]
R_i	- speed regulation due to governor action	=	2.40 [Hz p.u. MW^{-1}]
B_i	- frequency bias constant	=	0.425 [p.u. MW/Hz]
D_i	- load-frequency constant	=	0.0083 [p.u. MW/Hz]
P_{tie-m}	- maximum tie-line power handling capacity	=	200 [MW]
T_w	- water starting time constant	=	1.0 [s]
T_R	- hydro governor time constants	=	5.0 [s]
T_1		=	48.7 [s]
T_2		=	0.513 [s]
a_{12}	- rated area power constant	=	$-P_{r1}/P_{r2}$
K_r	- high pressure turbine power fraction	=	0.50

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