DAMPING OF LOW FREQUENCY OSCILLATIONS IN A SINGLE MACHINE POWER SYSTEM USING UPFC BASED DAMPING AND FUZZY CONTROLLERS

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Abstract: *Low frequency electromechanical oscillations are inevitable characteristics of power systems and they greatly affect the transmission line transfer capability and power system stability. PSS and FACTS devices can help the damping of power system oscillations. The objective of this paper is to propose a systematic approach for damping controller design for FACTS devices. Unified Power Flow Controller (UPFC) is a well-known FACTS device that can control power flow in transmission lines. It can also replace PSS to damp low frequency oscillations effectively through direct control of voltage and power. In this paper a linear Heffron-Philips model of a Single Machine Infinite Bus system with a unified power flow controller is developed. A proposed fuzzy logic based UPFC controller adjusts four UPFC inputs by appropriately processing of the input error signal, and provides an efficient damping when compared to conventional damping controller and PID controller. The simulations are performed in MATLAB/SIMULINK environment with necessary command lines. The results of the simulation show that the UPFC with fuzzy-based controllers is more effective in damping LFO compared to UPFC with damper controllers and PID controllers.*
Keywords: *Flexible AC Transmission Systems (FACTS), Low frequency oscillations (LFO), Single Machine Infinite Bus (SMIB), Unified Power Flow Controller (UPFC), damping controller.*

1. INTRODUCTION

In an interconnected power system, the synchronous generators should rotate at the synchronous speed and power flows over tie-lines should remain constant under normal operating conditions. However, low frequency electromechanical oscillations may occur when a disturbance is applied to the power system. These oscillations can be resembled in the power system variables like bus voltage, line current, generator speed and power. Originally, the fairly closely connected generators were observed to swing against each other at frequencies of around 1-2 Hz. The power transfer in an integrated power system is constrained by transient stability, voltage stability and small signal stability. These constraints limit the full utilization of available transmission corridors. Flexible AC Transmission Systems (FACTS) is the technology that provides the needed corrections of the transmission functionality in order to fully utilize the existing facilities. Unified Power Flow Controller (UPFC) is one of the FACTS devices, which can control three power system parameters like terminal voltage, line impedance and phase angle. Therefore, it can be used not only for power flow control but also for the power system stabilizing control. In this paper a linear Heffron-Philips model of a Single Machine–Infinite Bus system with a unified power flow controller is developed. A proposed fuzzy logic based UPFC controller adjusts four UPFC inputs by appropriately processing of the input error signal, and provides an efficient damping when compared to conventional damping controller and PID controller.

2. MODELING OF SINGLE MACHINE INFINITE BUS SYSTEM WITH UPFC

The schematic diagram of the power circuit of a single-phase UPFC which is composed of an excitation transformer (ET), a boosting transformer (BT), two three phase GTO based voltage source converters (VSCs), and a dc link capacitor is shown in figure 1.The four input control signals to the UPFC are m_E, m_B, δ_E and δ_B. Where m_E is the excitation amplitude modulation ratio, m_B is the boosting amplitude modulation ratio, δ_E is the excitation phase angle and δ_B is the boosting phase angle [1].

The UPFC can be modeled by applying Park's transformation and neglecting the resistances and transients of the excitation and boosting transformers [1-6]. The d-q axes voltage components of excitation transformer (E.T) and boosting transformer (B.T) are given in the following equations.

$$\begin{bmatrix} v_{Ed} \\ v_{Eq} \end{bmatrix} = \begin{bmatrix} 0 & -x_E \\ x_E & 0 \end{bmatrix} \begin{bmatrix} i_{Ed} \\ i_{Eq} \end{bmatrix} + \begin{bmatrix} \frac{m_E \cos\delta_E v_{dc}}{2} \\ \frac{m_E \sin\delta_E v_{dc}}{2} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} v_{Bd} \\ v_{Bq} \end{bmatrix} = \begin{bmatrix} 0 & -x_B \\ x_B & 0 \end{bmatrix} \begin{bmatrix} i_{Bd} \\ i_{Bq} \end{bmatrix} + \begin{bmatrix} \frac{m_B \cos\delta_B v_{dc}}{2} \\ \frac{m_B \sin\delta_B v_{dc}}{2} \end{bmatrix} \quad (2)$$

$$\dot{v}_{dc} = \frac{3m_E}{4C_{dc}}[\cos\delta_E \ \sin\delta_E] \begin{bmatrix} i_{Ed} \\ i_{Eq} \end{bmatrix} + \frac{3m_B}{4C_{dc}}[\cos\delta_B \ \sin\delta_B] \begin{bmatrix} i_{Bd} \\ i_{Bq} \end{bmatrix} \quad (3)$$

Where v_E, i_E, v_B and i_B are the excitation voltage, excitation current, boosting voltage and boosting current respectively. V_{dc} *is* the dc link capacitor voltage.

3. DESIGN OF DAMPING CONTROLLERS

The damping controllers are designed to produce an electrical torque in phase with the speed deviation. The four control parameters of the UPFC i.e., m_E, m_B, δ_E and δ_B can be modulated in order to produce the damping torque. The speed deviation $\Delta\omega$ is considered as the input to the damping controllers. The four alternatively UPFC based damping controllers are examined in this work. Damping controller based on UPFC control parameters m_B shall henceforth by denoted as damping controller (m_B). Similarly damping controllers based on m_E, δ_E and δ_B shall be denoted as damping controller (m_E), damping controller (δ_E) and damping controller (δ_B) respectively. The structure of UPFC based damping controller is shown in figure 2. It consists of gain, signal washout and phase compensator blocks. The parameters of the damping controller are obtained using the phase compensation technique [8].

The detailed step-by-step procedure for computing the parameters of the damping controllers using phase compensation technique is given as follows

- The natural frequency of oscillation ω_n from the mechanical loop are computed as $\omega_n = \sqrt{K_1 \omega_n / M}$
- Let the Phase lag between Δu and ΔP_e at $s = j\omega_n$ is $\angle GEPA = \gamma$.
- The phase lead-lag compensator Gc is designed to provide the required degree of phase compensation. For 100% phase compensation $\angle Gc(j\omega_n) + \angle GEPA(j\omega_n) = 0$. Assuming one lead-lag network, $T_1 = aT_2$, the transfer function of the phase compensator be $Gc(s) = 1 + saT_2 / 1 + sT_2$, since the phase angle compensated by the lead-lag network is equal to $-\gamma$. The parameters a and T_2 are computed as, $a = 1 + \sin\gamma / 1 - \sin\gamma$, $T_2 = 1 / \omega_n \sqrt{a}$
- The optimal gain K_{dc} for the desired value of damping ratio $(\zeta = 0.5)$ is obtained as $K_{dc} = 2\zeta\omega_n M / |Gc(s)||GEPA(s)|$, where $|Gc(s)|$ and $|GEPA(s)|$ are evaluated at $s = j\omega_n$.

The signal washout is the high pass filter that prevents steady changes in the speed from modifying the UPFC input parameters. The value of the washout time constant T_w should be high enough to allow signals associated with oscillation in rotor speed to pass unchanged. From the viewpoint of the washout function, the value of T_w is not critical may be in the range of 1s to 20s. T_w = 10s is chosen for the present case.

Figure 3 shows the transfer function of the system relating component of electrical power (ΔP_e) produced by damping controller (m_B). The time constants of the phase compensator are chosen so that the phase lead-lag of the system is fully compensated. For the nominal operating conditions, the natural frequency of oscillation ω_n =4.122rad/sec. the transfer function relating ΔP_e and Δm_B is denoted as GEPA. For the nominal operating condition, phase angle of

GEPA i.e., $\angle GEPA$ =9.0527^0 lagging. The magnitude of GEPA is $|GEPA|$=0.6789. To compensate the phase lead, the time constants of the compensator are obtained as T_1=0.2860Sand T_2=0.2082S.

The phase angle to be compensated by the other three damping controllers are computed in the same approach and are given in table 1.

Table 1 Gain and phase angle of the transfer function GEPA

GEPA	$\lvert GEPA \rvert$	$\angle GEPA$
ΔPe/ΔmE	1.5891	-18.38050
ΔPe/ΔδE	1.9251	3.48360
ΔPe/ΔmB	0.6789	-9.05270
ΔPe/ΔδB	0.0923	4.25710

Table 2 Parameters of UPFC based damping controllers

Damping controller	K_{dc}	T1,s	T2,s
(mE)	14.8813	0.3383	0.1761
(δE)	18.0960	0.2296	0.2516
(mB)	41.1419	0.2860	0.2082
(δB)	382.4410	0.2266	0.2694

The critical examination of Table 1 reveals that the phase angle of the system i.e., $\angle GEPA$, is leading for control parameter δ_E and δ_B. However, it is lagging for m_E and m_B. Hence the phase compensator for the damping controller (δ_E) and damping controller (δ_B) is a lag compensator while for the damping controller (m_E) and damping controller (m_B) is a lead compensator. The gain settings (K_{dc}) of the controllers are computed assuming a damping ratio $\zeta = 0.5$. Table 2 shows the parameters (gains and time constants) of the four alternative damping controllers. It shows the gain settings of the damping controller (m_E) and damping controller (δ_E) doesn't differ much. However, the gain setting of the damping controller (δ_B) is much higher as compared to the damping controller (m_B).

4. PERFORMANCE WITH UPFC DAMPER CONTROLLERS

The simulation model of single machine infinite bus system incorporated with UPFC damping controller m_B is shown in Figure 4. The damping parameters of the controller are computed and given in Table 2. The variation of angular speed $\Delta\omega$ with time for 0.02 p.u step change in mechanical power input P_m with four alternative damping controllers is shown in figure 5. The dynamic responses shown in Figure 5 are obtained for $\Delta\omega$ considering a step load perturbation $\Delta P_m = 0.02\,pu$ with the four alternative damping controllers. At this stage it can be inferred that any of the UPFC based damping controllers provide satisfactory dynamic performance at the nominal operating condition. From the dynamic responses it is observed that δ_B and δ_E is more dominant compared to m_B and m_E in terms of overshot and settling time.

5. FUZZY LOGIC CONTROLLER FOR DAMPING OSCILLATAIONS

Fuzzy control is based on fuzzy logic, which provides an effective way to capture the operator's experiences and knowledge in the form of IF-THEN rule. This kind of logic provides an alternative way to deal with the problems that are usually raised when someone tries to model or design controllers for complex systems.

Fuzzy logic controller structure:
The main task of fuzzy logic controller structure is to generate an adequate control decision that can be described by linguistic rules. The general configuration of a fuzzy logic controller is composed of four modules [14], which are shown in Figure.6

1. Fuzzification module
2. Knowledge base module
3. Inference engine module
4. Defuzzification module

Before designing these four modules, we need to select the FLC input variables. There are two signals that most of the designers used: error and rate. The objective of using these two signal are to keep the error signal as small as possible and to make sure that the error is decreasing. PI or PD fuzzy type controllers are most commonly used controllers. Other inputs may be added to make the FLC more robust.

Fuzzification Module
Fuzzification is the first operation to be performed, and it involves transferring the range of the inputs (e.g., error (x_1) and error rate (x_2)) and output variables of the FLC into their corresponding universe of discourse. The second operation is to divide these universe of discourses into suitable linguistically

fuzzy variables such as positive and negative. The inputs and output variables determine which states of the process are to be observed and which control actions are to be considered. For FLC design, generator speed deviation and rotor angle deviation have been observed as the input variables. The modulation amplitudes or phase angles of shunt or a series converters were chosen to be the output variable from the FLC. The dynamic performance of the system could be evaluated by examining the response curves of these two variables. The membership functions are shown in figures 7 and 8. The number of linguistic variables describing the fuzzy subsets of a variable varies according to the application. Usually an odd number of membership functions are used. Each linguistic variable has its fuzzy membership function. The membership function maps the crisp values into fuzzy variables. The triangular membership functions with 50% overlap between the adjacent fuzzy subsets. Each of the input and output fuzzy variables is assigned seven linguistic fuzzy subsets varying from negative big (NB) to positive big (PB). Each subset is associated with a triangular membership function to form a set of seven membership function for each fuzzy variable.

Table 3 Membership functions for fuzzy variables

NB	NEGATIVE BIG
NM	NEGATIVE MEDIUM
NS	NEGATIVE SMALL
Z	ZERO
PS	POSITIVE SMALL
PM	POSITIVE MEDIUM
PB	POSITIVE BIG

Knowledge base module:

The knowledge base consists of two components: a database and a rule base. The former has its basic function provision of necessary information to the rule base and, the fuzzification module, defuzzification modules. The basic function of the rule base is to represent structurally the control policy in the form of a set of fuzzy rules.

Database:

The main function of the database is to provide the required necessary information to other modules in order to allow them proper functionality. The information that the database should provide is: the fuzzy set and their membership functions together with the meaning of linguistics values and, the physical domains and their normalized counterparts.

Rule base Module

A set of rules which define the relation between the input and output of fuzzy controller can be found using the available knowledge in the area of designing FLC. These rules are defined using the linguistic variables. The two inputs results 49 rules for each system.

Table 4 Rule base of fuzzy controller

	LN	MN	SN	Z	SP	MP	LP
LN	PB	PB	PB	PM	PM	PS	Z
MN	PB	PB	PM	PM	PS	Z	NS
SN	PB	PM	PM	PS	Z	NS	NM
Z	PM	PM	PS	Z	NS	NM	NM
SP	PM	PS	Z	NS	NM	NM	NB
MP	PS	Z	NS	NM	NM	NB	NB
LP	Z	NS	NM	NM	NB	NB	NB

The Mamdani Model:

Mamdani type has both input and output variables fuzzified by fuzzy membership functions [13]. It is considered the most popular method that is used to design FLC, because it is simple to implement and has fewer variables to specify than Takagi-Sugeno method. Let us now take FLC with two inputs and one output to show the form of mamdani fuzzy rules.

Rule1: if x_1 is NM and x_2 is PS then u is NS
Rule2: if x_1 is Z and x_2 is NB then u is NM
Rule3: if x_1 is PS and x_2 is NS then u is Z

Where x_1 and x_2 are linguistic variables representing process state variables.

The number of rules can be increased if we increase the number of the linguistic variables.

.Inference Module

The basic function of the inference engine is to compute the overall value of the control output variable based on the individual contributions of each rule in the rule base. Each such individual contribution represents the value of the control output variables computed by a single rule. The fuzzy inference engine evaluates the control rules stored in the rule base. It has four main tasks: rule firing, strength calculation, fuzzy implication and rule aggregation. The result of the inference engine is one or several output fuzzy sets, whose membership functions are defuzzified to obtain the control action. The output represents the degree of relationship between the input and each output fuzzy set.

Defuzzification:

Defuzzification performs scale mapping, which converts the range of values of output variables into corresponding universe of discourse, it yields a non-fuzzy control action from an inferred control action. The different methods of Defuzzification are max criterion method, mean of maxima method and centroid method etc.

Center of Area method:

The widely used COA strategy generates the center of gravity of the possibility distribution of a control action

$$u = \frac{\sum_i \mu(x_i)\ x_i}{\sum_i \mu(x_i)}$$

Here x_i is a running point in the universe of discourse, and $\mu(x_i)$ is its membership value in the membership function. The expression can be interpreted as weighted average of the elements in the support set. For the continuous case, replace the summation by integrals. This method is most commonly used although its computational complexity is relatively high. This is also known as center of gravity method.

6. IMPLEMENTATION OF FUZZY LOGIC BASED UPFC CONTROLLER

In order to damp out low frequency oscillations effectively, fuzzy lozic controllers are designed for UPFC inputs. In the proposed method, Mamdani's fuzzy inference method is used, because it is the most commonly employed fuzzy methodology [9-11]. After the aggregation process, there is a fuzzy set for each output variable and finally they need to be defuzzificated. Angular velocity deviation ($\Delta\omega$) and load angle deviation ($\Delta\delta$) are used as the fuzzy controllers inputs. One of the UPFC parameters (m_B, m_E, δ_B and δ_E) has been controlled through fuzzy controller. Figure 9 shows the block diagram for fuzzy logic based power system with UPFC controller m_B. Mamdani's fuzzy inference method is used in the test system, because it is the most commonly employed fuzzy methodology [9]. Angular velocity deviation $\Delta\omega$ and load angle deviation $\Delta\delta$ used as the fuzzy controllers inputs. Figure 10 shows the dynamic responses for angular speed $\Delta\omega$ with time for 0.02 p.u step change in mechanical power input P_m with four alternative controllers. From the dynamic responses it is observed that δ_B and δ_E are more dominant compared to m_B and m_E.

7. COMPARISON OF CONTROLLER PERFORMANCE WITH DIFFERENT CONTROL PAPRAMETERS

During step change in mechanical power (ΔP_m=0.02 p.u), performance of the designed fuzzy logic controllers, PID controllers and damper controllers have been simulated and compared. The simulation is performed using MATLAB/SIMULINK software. The simulation is performed with the step change in mechanical input power, but the UPFC has controller for different cases.

In the first case the UPFC is equipped with the damper controller and in the second case the UPFC is provided with conventional PID controller and finally the UPFC is equipped with fuzzy controller. The results of simulation with controller m_E for the three cases are shown in figure 11. The simulations are performed by controlling the input m_E of the UPFC. Figures 12, 13 and 14 shows the output of the designed controller for δ_E, m_B and δ_B UPFC inputs respectively. Simulation results show that fuzzy logic controller successfully increases damping rate and decreases the amplitude of low frequency oscillations. Results comparison between damper controllers, conventional PID controller and the proposed fuzzy for the UPFC indicates that the proposed fuzzy controller has less settling time and less overshoot and compared with the other controllers.

8. CONCLUSIONS

The objective of this work is to damp the oscillations of the power system using a fuzzy logic theory on single machine infinite bus system with UPFC. The proposed controller provides a more robust control over the conventional damping and PID controllers. In this thesis the effect of damping controllers (phase compensation) and PID controllers in damping the power system oscillations are reviewed then the fuzzy based controller is introduced with angular speed deviation $\Delta\omega$ and rotor angle deviation $\Delta\delta$ of the generator as input signals to the fuzzy controller and one of the UPFC control parameter $m_E, m_B, \delta_B, \delta_E$ as output signal. From the simulations it is studied that fuzzy based δ_B and δ_E control parameters provides dominant performance compared to other control parameters like m_B and m_E at the given operating condition and system parameters.

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Appendix

Design data for the test system

Generator:

$M = 2H = 8.0 MJ / MVA \quad D = 0 \quad T'_{do} = 5.044s$

$X_d = 1.0 \quad X_q = 0.6 \quad X'_d = 0.3$

Excitation system:

$K_a = 100 \quad T_a = 0.01s$

Transformer:

$X_{tE} = 0.1 p.u \quad X_E = X_B = 0.1 p.u$

Transmission line:

$X_{Bv} = 0.3 p.u \quad X_e = 0.5 p.u$

Operating condition:

$P_e = 0.8 \quad V_t = 1.0 p.u \quad V_b = 1.0 p.u$

$f = 50Hz$

UPFC parameters:

$m_E = 0.4013 \quad m_B = 0.0789 \quad \delta_E = -85.3478°$

$\delta_B = -78.2174°$

Parameters of DC capacitor link:

$V_{dc} = 2.0 p.u \quad C_{dc} = 1.0 p.u$

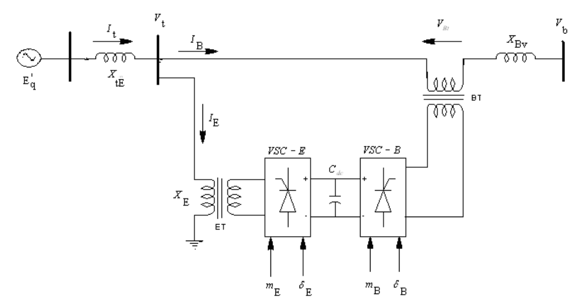

Fig.1 UPFC installed in single machine infinite bus system

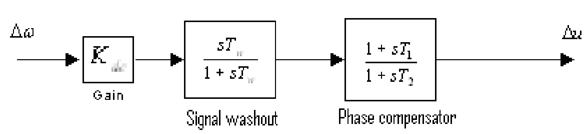

Fig.2 Structure of UPFC based damping controller

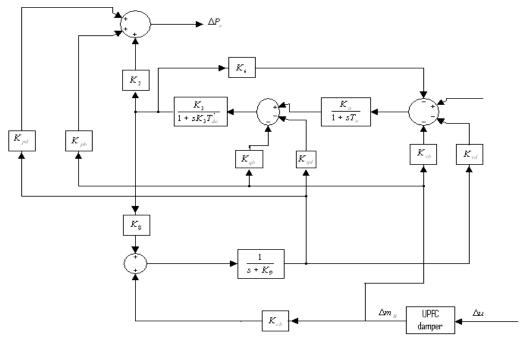

Fig.3 The transfer function of the system relating component of electrical power (ΔP_e) produced by damping controller (m_B)

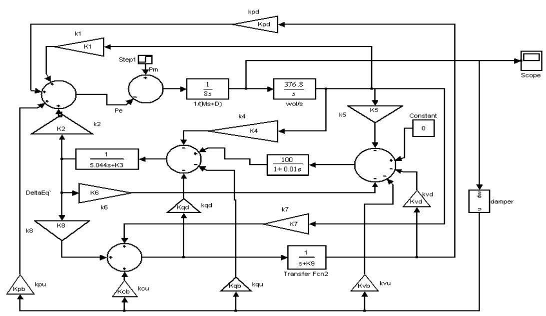

Fig.4 Simulation model of SMIB system with UPFC damper controller

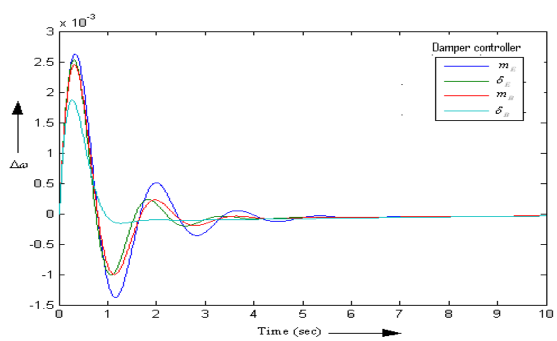

Fig.5 Dynamic responses for $\Delta\omega$ four alternative damping controllers

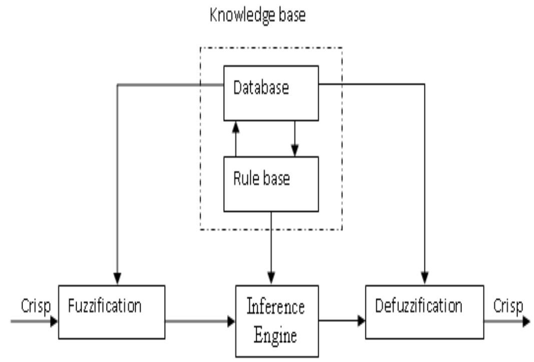

Fig.6 Schematic diagram for the fuzzy logic controller

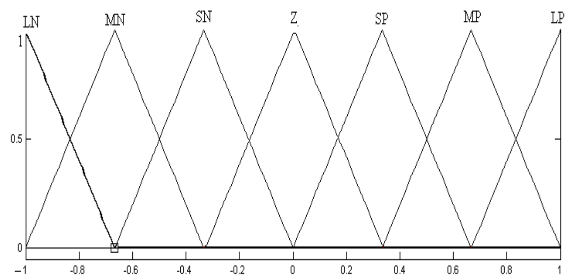

Fig.7 Input Membership functions

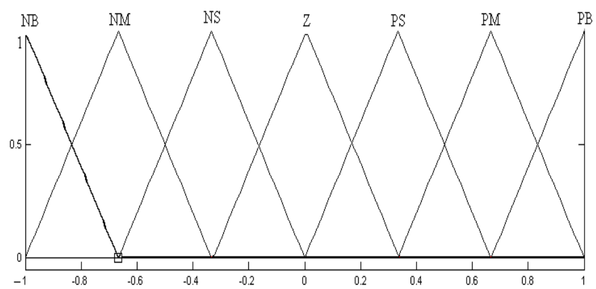

Fig.8 Output Membership functions

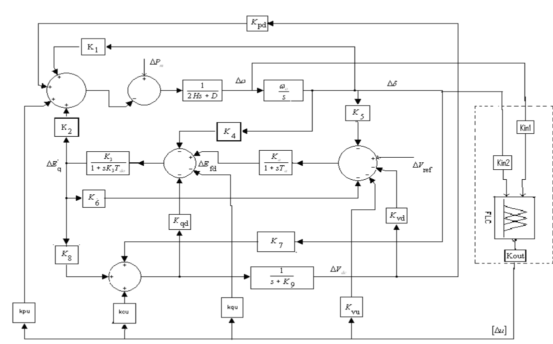

Fig.9 Block diagram of modified Heffron-Phillips model with fuzzy logic controller

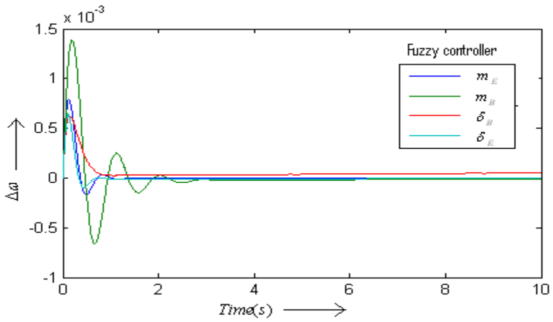

Fig.10 Dynamic responses for $\Delta\omega$ with time for 0.02 p.u change in mechanical power input with four alternative controllers

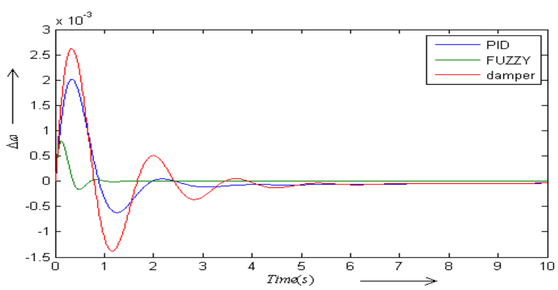

Fig.11 Dynamic response for $\Delta\omega$ with controller m_E

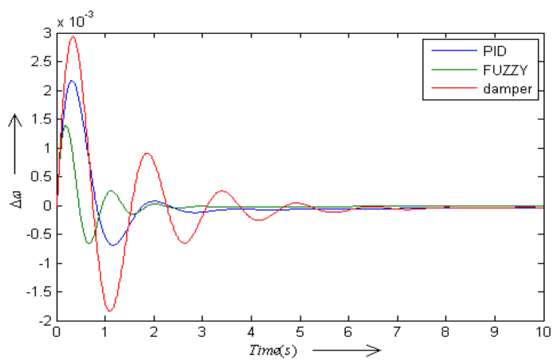

Fig.12 Dynamic response for $\Delta\omega$ with controller m_B

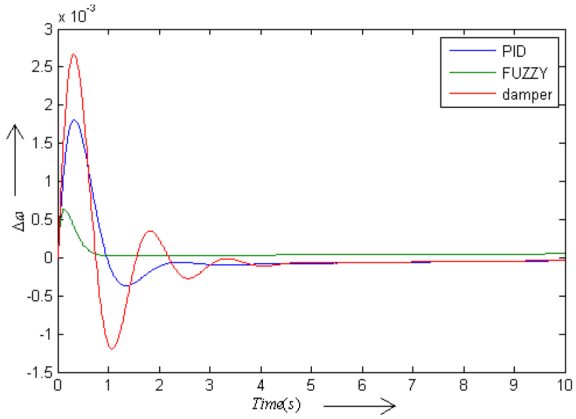

Fig.13 Dynamic response for $\Delta\omega$ with controller δ_B

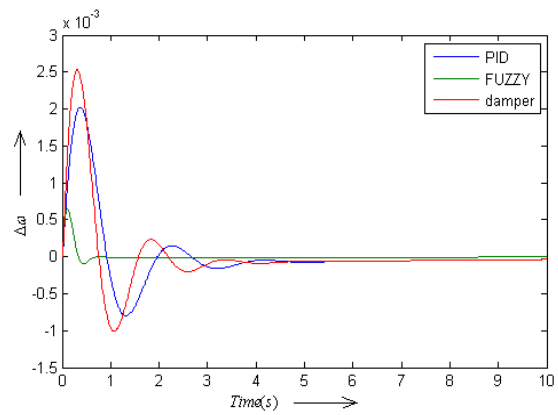

Fig.14 Dynamic response for $\Delta\omega$ with controller δ_E