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Fuzzy Logic Based UPFC Controller for Damping Power System Oscillations

Senthil Kumar N*

In this paper, a fuzzy logic controller is proposed for a Unified Power Flow Controller (UPFC) installed in a single-machine infinite-bus power system. The Fuzzy Logic controller is mainly equipped to damp power system oscillations. Simple Fuzzy Logic controller using mamdani-type inference system is used. The Fuzzy Logic based UPFC controller is designed by selecting appropriate controller parameters based on the knowledge of the power system performance. The effectiveness of the new controller is demonstrated through time-domain simulation studies. By comparison, it can be seen that the proposed UPFC controller can provide good performance for different operating conditions of power system. The results of these studies show that the designed controller is robust enough to damp power system oscillations with change in system operating conditions.

Keywords: *FACTS, UPFC, Fuzzy Logic, Power System Oscillations*

1.0 INTRODUCTION

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 system (FACTS) is the technology that provides the needed corrections of the transmission functionality in order to fully utilize the existing transmission facilities and hence, minimize the gap between the stability limit and thermal limit. As one of the most versatile FACTS devices, unified power flow controller (UPFC) can provide simultaneous control of both real and reactive power flow in the line.

Unified power flow controller (UPFC) is one of the FACTS devices, which can control power system parameters such as terminal Voltage, line impedance and phase angle [1-3]. Therefore, it can be used not only for power flow control, but also for power system stabilizing control.

Recently researchers have presented dynamic models of UPFC in order to design suitable controllers for power flow, voltage and damping controls. Wang, [6-8] has presented a modified linearized Heffron Phillips model of a power system installed with UPFC.

The main objectives of the present research work presented in the paper are,

1. To present a systematic approach for fuzzy based UPFC damping controllers.
2. To investigate the performance and comparative analysis of damping controllers, following wide variations in loading conditions and system parameters.

2.0 SYSTEM INVESTIGATED

A single-machine-infinite-bus (SMIB) system is shown in Figure 1 [11]. The static excitation system model type IEEE- ST1A has been considered. The UPFC considered here is assumed to be based on

* Associate professor, School of Electrical Engineering, VIT University, Chennai Campus.chennai-600 127. Mobile: +91 9444242263
Email: senthilkumar.nataraj@vit.ac.in

pulse width modulation (PWM) converters and connected in circuit 2 of the system between the HT bus and the infinite bus.

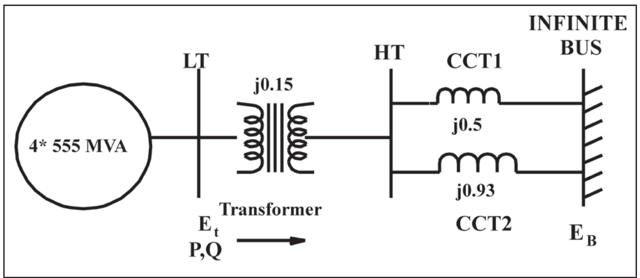

FIG. 1 SINGLE MACHINE INFINITE BUS SYSTEM

3.0 UNIFIED POWER FLOW CONTROLLER

Unified power flow controller (UPFC) is a combination of static synchronous compensator (STATCOM) and a static synchronous series compensator (SSSC) which are coupled via a common dc link, to allow bi-directional flow of real power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM and are controlled to provide concurrent real and reactive series line compensation without an external electric energy source. The UPFC, by means of angularly constrained series voltage injection, is able to control, concurrently or selectively, the transmission line voltage, impedance and angle or alternatively, the real and reactive power flow in the line. The UPFC can also be utilized for damping power-system oscillations. Steady state and dynamic models of UPFC have been developed by several researchers [4–5]. Wang has developed modified linearized Heffron-Phillips model for an SMIB system with UPFC installed.

4.0 NONLINEAR DYNAMIC MODEL OF THE SMIB SYSTEM WITH UPFC

A non-linear dynamic model of the system is derived by disregarding the resistance of all the components of the system and transients of the transmission lines and transformers of the UPFC [9]. The dynamic equation of the single machine infinite bus system (SMIB) with the UPFC is given below:

$$\dot{\omega} = \frac{(P_m - P_e - D\Delta\omega)}{M} \quad ....(1)$$

$$\dot{\delta} = \omega_0(\omega - 1) \quad ....(2)$$

$$\dot{E}q' = \frac{(-E_q + E_{fd})}{T_{do}'} \quad ....(3)$$

$$\dot{E}_{fd} = \frac{-E_{fd} + K_a(V_{ref} - V_t)}{T_a} \quad ....(4)$$

$$\dot{V}_{dc} = \frac{3m_E}{4C_{dc}}(\sin(\delta_E)I_{Ed} + \cos(\delta_E)I_{Eq}) + \frac{3m_B}{4C_{dc}}(\sin(\delta_B)I_{Bd} + \cos(\delta_B)I_{Bq}) \quad ....(5)$$

where,

$$P_e = V_{td}I_{td} + V_{tq}I_{tq}\ ,\ E_q = E_q' + (X_d - X_d')\, I_{td}$$
$$V_t = V_{td} + jV_{tq}\ ,\ V_{td} = X_q I_{tq} \quad ....(6)$$

4.1 Linear dynamic model

A linear dynamic model is obtained by linearizing the non-linear model eqn.(1) to (5) around an operating condition [9]. The linearized model is given below:

$$\Delta\dot{\omega} = \frac{(\Delta P_m - \Delta P_e - D\Delta\omega)}{M} \quad ....(7)$$

$$\Delta\dot{\delta} = \omega_0\Delta\omega \quad ....(8)$$

$$\Delta\dot{E}q' = \frac{(-\Delta E_q + \Delta E_{fd})}{T_{do}'} \quad ....(9)$$

$$\Delta\dot{E}_{fd} = \frac{-\Delta E_{fd} + K_a(\Delta V_{ref} - \Delta V_t)}{T_a} \quad ....(10)$$

$$\Delta\dot{V}_{dc} = K_7\Delta\delta + K_8\Delta Eq' - K_9\Delta V_{dc} + K_{ce}\Delta m_E + K_{c\delta e}\Delta\delta_E + K_{cb}\Delta m_B + K_{c\delta b}\Delta\delta_B \quad ....(11)$$

where

$\Delta P_e = K_1\Delta\delta + K_2\Delta E'_q + K_{pe}\Delta m_E + K_{p\delta e}\Delta\delta_E + K_{pb}\Delta m_B + K_{p\delta b}\Delta\delta_B + K_{pd}\Delta V_{dc}$

$\Delta E_q = K_4\Delta\delta + K_3\Delta E'_q + K_{qe}\Delta m_E + K_{q\delta e}\Delta\delta_E + K_{qb}\Delta m_B + K_{q\delta b}\Delta\delta_B + K_{qd}\Delta V_{dc}$

$\Delta V_t = K_5\Delta\delta + K_6\Delta E'_q + K_{ve}\Delta m_E + K_{v\delta e}\Delta\delta_E + K_{vb}\Delta m_B + K_{v\delta b}\Delta\delta_B + K_{vd}\Delta V_{dc}$

for detailed derivation of K - constant computations refer [9].

4.2 Dynamic model of UPFC in Single Machine Infinite Bus System in state-space form

The dynamic model of the system in state-space form is

$$\dot{X} = AX + Bu$$
$$X = [\Delta\delta \;\; \Delta\omega \;\; \Delta E_q' \;\; \Delta E_{fd} \;\; \Delta V_{dc}]^T; \qquad ....(12)$$
$$u = [\Delta m_E \;\; \Delta\delta_E \;\; \Delta m_B \;\; \Delta\delta_B]^T$$

where

Δm_B: deviation in pulse width modulation index mB of series inverter.

$\Delta\delta_B$: deviation in phase angle of the injected voltage

Δm_E : deviation in phase-width-modulation index mE of the shunt inverter.

$\Delta\delta_E$: deviation in phase angle of the shunt - inverter voltage.

$$A = \begin{bmatrix} 0 & \omega_0 & 0 & 0 & 0 \\ \frac{-K_1}{M} & 0 & \frac{-K_2}{M} & 0 & \frac{-K_{pd}}{M} \\ \frac{-K_4}{T'_{do}} & 0 & \frac{-K_3}{T'_{do}} & \frac{1}{T'_{do}} & \frac{-K_{qd}}{T'_{do}} \\ \frac{-K_a K_5}{T_a} & 0 & \frac{-K_a K_6}{T_a} & \frac{1}{T_a} & \frac{-K_a K_{td}}{T_a} \\ K_7 & 0 & K_8 & 0 & -K_9 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 \\ \frac{-K_{pe}}{M} & \frac{-K_{p\delta e}}{M} & \frac{-K_{pb}}{M} & \frac{-K_{p\delta b}}{M} \\ \frac{-K_{qe}}{T'_{do}} & \frac{-K_{q\delta e}}{T'_{do}} & \frac{-K_{qb}}{T'_{do}} & \frac{-K_{q\delta b}}{T'_{do}} \\ \frac{-K_a K_{ve}}{T_a} & \frac{-K_a K_{v\delta e}}{T_a} & \frac{-K_a K_{vb}}{T_a} & \frac{-K_a K_{vb}}{T_a} \\ K_{ce} & K_{c\delta e} & K_{cb} & K_{c\delta b} \end{bmatrix}$$

By controlling m_B, the magnitude of series-injected voltage can be controlled. By controlling m_E, the output voltage of the shunt converter is controlled. The series and shunt converters are controlled in a coordinated manner to ensure that the real power output of the shunt converter is equal to the real power input to the series converter. The fact that the DC voltage remains constant ensures that this equality is maintained.

5.0 CONVENTIONAL DAMPING CONTROLLER DESIGN

The damping controllers are designed taking ΔmB and ΔδE as their output signals. The speed deviation signal dδ/dt which has been derived is used as an input to the damping controller. The transfer function block diagram of the damping controller is shown in Figure 2. It comprises gain block, signal – washout block and lead lag compensator. The value of washout time constant Tw is not critical and may be chosen in the range of 1 to 20 seconds. [9]

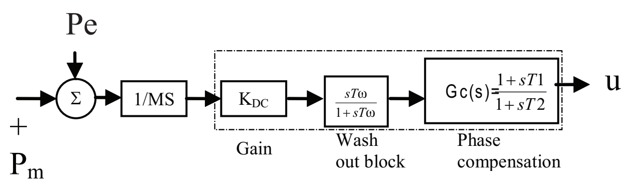

FIG.2 TRANSFER FUNCTION OF UPFC BASED CONVEΔNTIONAL DAMPING CONTROLLER

5.1 Fuzzy logic controller Design:

A simple fuzzy logic controller based on mamdani type is used in this section in place of conventional damping controller to damp power system oscillations in the study system. The fuzzy logic controller uses generator angular speed and deviation of angular speed as controller input signal. Two-input one-output proportional fuzzy logic controller is shown in the Figure 3. The membership functions of the input and output signals are shown in Figure 5.

5.2 Evaluation of linguistic variables:

For the selection of number of linguistic variables, two linguistic rule tables, four linguistic rule tables and five linguistic rule tables were considered. Five linguistic rule base provided better performance over the other two. The inputs are described by five linguistic variables: NB (negative big), NS (negative small), Z (Zero), PS (Positive small) and PB (positive big). The output is described by nine linguistic variables NVB (Negative very big), NB (Negative big), NM (Negative medium), NS (Negative small), Z(zero), PS (Positive small), PM (Positive medium), PB (positive big), PVB (Positive very big). Triangular membership function for both inputs and output was chosen. The rule table used in this controller is given in Table 1.

TABLE 1
RULE BASE USED FOR FUZZY CONTROLLER

$\Delta\omega$ \ $\Delta\acute{\omega}$	NB	NS	Z	PS	PB
NB	NVB	NB	NM	NS	Z
NS	NB	NM	NS	Z	PS
Z	NM	NS	Z	PS	PM
PS	NS	Z	PS	PM	PB
PB	Z	PS	PM	PB	PVB

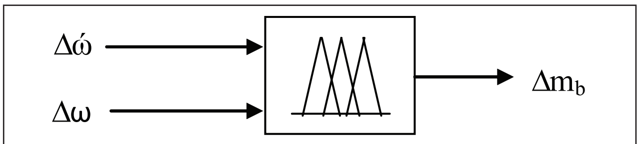

FIG. 3 FUZZY LOGIC CONTROLLER STRUCTURE

5.2.1 Evaluation of degree of Overlap:

In the fuzzy logic the degree of overlap should be properly chosen such that to obtain the desired output from the controller. There is no systematic design procedure for this estimation. The fuzzy membership function is being modified for three different degree of overlap, such as no-overlap, 1/2 overlap and 1/3 overlap. For evaluation of degree of overlap, normal operating condition is considered and simulation is performed for different membership function.

Normal Load : $P_e = 0.918$pu; $Q_e = 0.277$pu

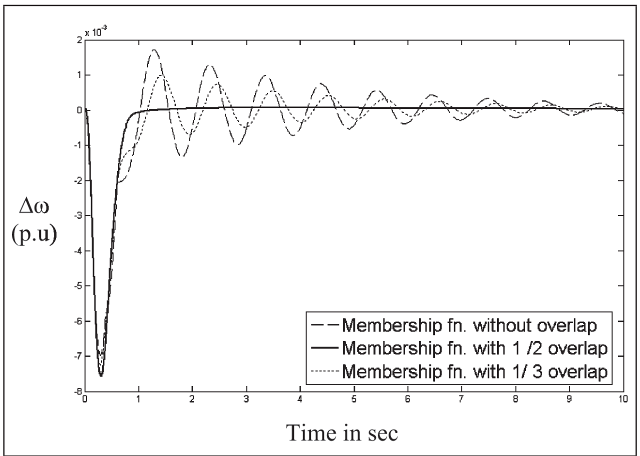

FIG. 4 COMPARITIVE ANALYSIS OF MEMBERSHIP FUNCTIONS

In the above case, it has been found that fuzzy controller having 1/2 overlap damps out quickly when compared to membership function with 1/3 overlap and without overlap. Hence for further study, fuzzy logic controller with 1/2 overlap is considered.

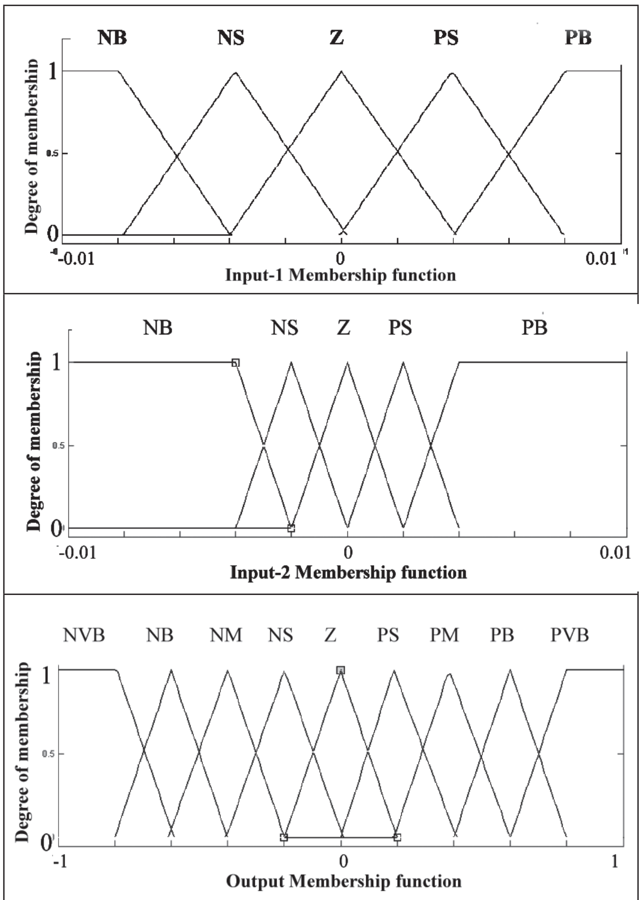

FIG. 5 I/P AND O/P MEMBERSHIP FUNCTIONS WITH 1/2 OVERLAP

5.3 Modified Heffron- Phillips small perturbation transfer function model of a SMIB system including UPFC with fuzzy logic controller

Figure 6 shows the small perturbation transfer function block diagram model of a single machine – infinite bus system including UPFC relating the pertinent variable of electric torque, speed, angle, terminal voltage, field voltage, flux linkage, UPFC control parameters, and dc link voltage.

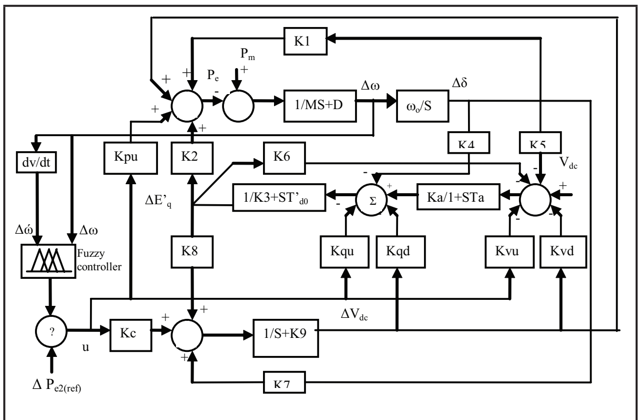

FIG. 6 HEFFRON – PHILLIPS MODEL OF SMIB SYSTEM WITH FUZZY LOGIC BASED UPFC CONTROLLER

6.0 EFFECT OF VARIATION OF LOAD CONDITIONS AND SYSTEM PARAMETERS ON THE DYNAMIC PERFORMANCE OF THE SYSTEM

In any power system, the operating load varies over a wide range randomly. It is extremely important to investigate the effect of variation of the loading conditions on the dynamic performance of the system. In order to examine the robustness of the UPFC based damping controller to wide variations in the system operating loads, three different operating conditions are taken viz. Heavy Load, Normal Load and Lighter Load conditions. The operating load is varied as mentioned above and the dynamic responses are obtained for each of the loading condition considering parameters of the damping controllers computed at nominal operating condition for the step load perturbation in mechanical power.

Heavy Load:

$P_e = 1.031$ p.u. $\Delta P_m = 0.01$pu

$Q_e = 0.364$ p.u $P_{e2ref} = 0.01$pu

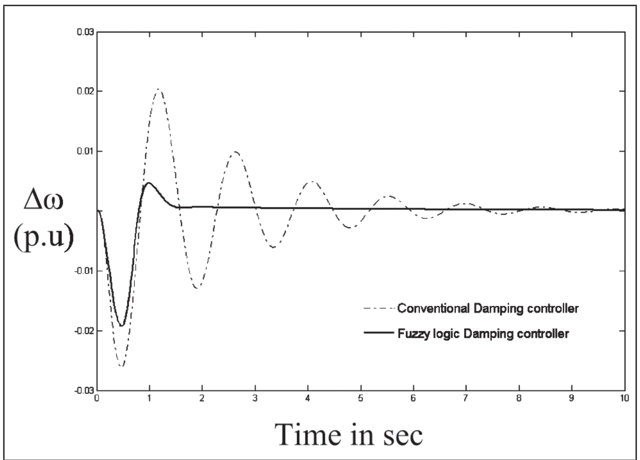

FIG. 7 DYNAMIC RESPONSE OF ΔΩ FOR CONVENTIONAL AND FUZZY LOGIC DAMPING CONTROLLER.

From the dynamic response it can be inferred that with conventional damping controller the peak undershoot is 0.09 p.u whereas with fuzzy logic based damping controller it is 0.019 p.u. The settling time has also reduced considerably with a fuzzy logic based damping controller to typically 1.8 seconds

The settling time has reduced by 81% using fuzzy logic controller.

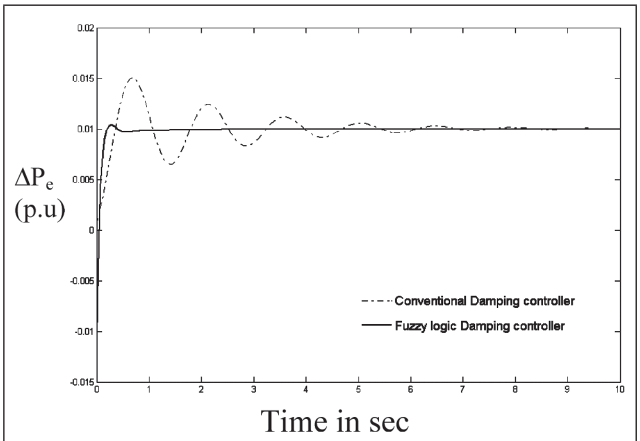

FIG. 8 DYNAMIC RESPONSE OF ΔP_e, FOR CONVENTIONAL AND FUZZY LOGIC DAMPING CONTROLLER.

Normal Load:

$P_e =$ 0.918 p.u. $\Delta P_m = 0.01$pu

$Q_e =$ 0.277 p.u $P_{e2ref} = 0.01$pu

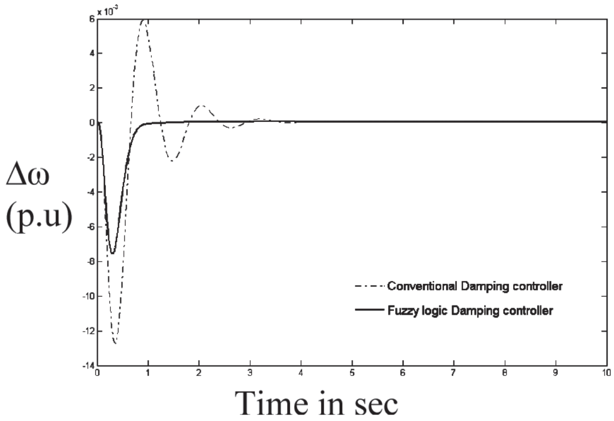

FIG. 9 DYNAMIC RESPONSE OF Δω WITH CONVENTIONAL AND FUZZY LOGIC BASED DAMPING CONTROLLER.

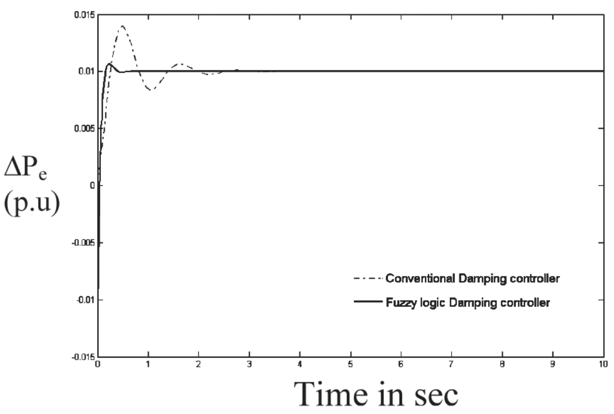

FIG. 10 DYNAMIC RESPONSE OF ΔP_E FOR CONVENTIONAL AND FUZZY LOGIC DAMPING CONTROLLER.

Light Load:

P_e = 0.651 p.u. ΔP_m = 0.01pu

Q_e = 0.135 p.u P_{e2ref} = 0.01pu

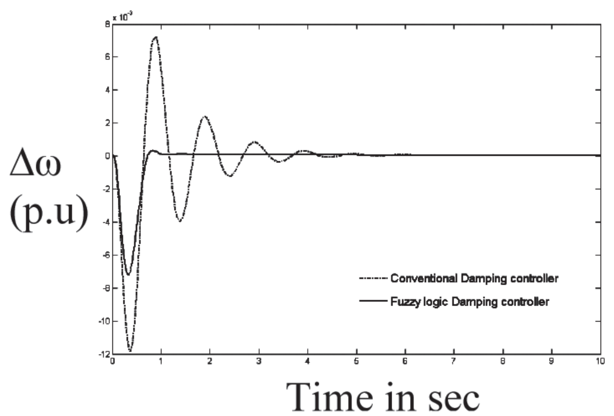

FIG. 11 DYNAMIC RESPONSE ΔΩ WITH CONVENTIONAL AND FUZZY LOGIC DAMPING CONTROLLER.

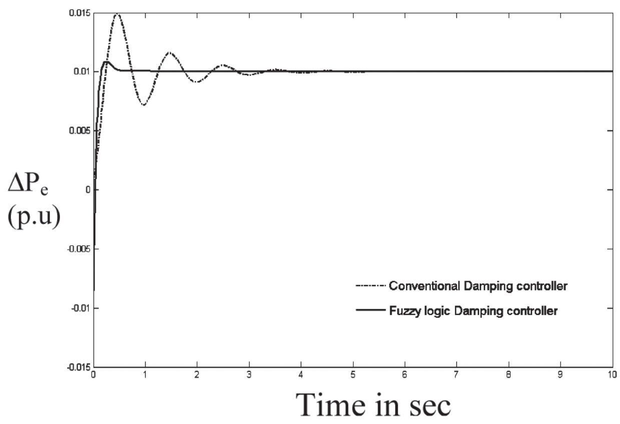

FIG. 12 DYNAMIC RESPONSE OF ΔP_E WITH CONVENTIONAL AND FUZZY LOGIC DAMPING CONTROLLER.

For the given extreme operating conditions, the fuzzy logic controller is found to be superior, compared to the conventional controller.

7.0 CONCLUSION AND FUTURE WORK

Establishment of the Linearized Heffron Phillips model of single-machine Infinite Bus Power system installed with a UPFC and to investigate the effectiveness of fuzzy logic based UPFC controller for damping power system oscillation. The performance of the fuzzy logic controller with 25 rule base is compared with the conventional damping controller under different loading conditions.

From the above studies, it can be concluded that the fuzzy logic based damping controller exhibits a robust dynamic performance as compared to that obtained with the conventional damping controller. The above work may be extended to multi-machine power systems, and the investigation may be carried out with different other possible membership functions.

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