International Journal of Electrical and Power Engineering 2 (5): 314-320, 2008
ISSN: 1990-7958

Low Frequency Oscillations Damping by UPFC with a Robust Fuzzy Supplementary Controller

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Abstract: This study presents discusses the small-signal stability analysis of the application of a unified power flow controller (UPFC) to enhance the damping of low frequency oscillation (LFO) in a single-machine infinite-bus (SMIB) power system. A UPFC supplementary damping controller design using a fuzzy logic schemes is considered to enhance damping. The advantages of the proposed method are their feasibility and simplicity. To show effectiveness of fuzzy approach in damping power system oscillation, the proposed method is compared with a conventional method (lead-lag compensation). Validity of the proposed method has been confirmed by linear time-domain simulation results.

Key words: Low Frequency Oscillation (LFO), Unified Power Flow Controller (UPFC), damping power system oscillations, Fuzzy Logic, Flexible AC Transmission Systems (FACTS)

INTRODUCTION

The flexible AC transmission systems (FACTS) based on power electronics offer an opportunity to enhance controllability, stability and power transfer capability of AC transmission systems (Hingorani and Gyugyi, 2000). The UPFC is one of the most complex FACTS devices in a power system today. It is primarily used for independent control of real and reactive power in transmission lines for flexible, reliable and economic operation and loading of power systems. Until recently all three parameters that affect real and reactive power flows on the line, i.e., line impedance, voltage magnitudes at the terminals of the line and power angle, were controlled separately using either mechanical or other FACTS devices such as static VAR compensators (SVC), thyristor controlled series capacitors (TCSC), etc (Hingorani and Gyugyi, 2000; Gyugyi *et al*., 1995; Gyugyi, 1992; Li *et al*., 2000; Gholipou and Saadat, 2005; Wang, 1999).

However, the UPFC allows simultaneous or independent control of all these three parameters, with possible switching from one control scheme to another in real time. Also, the UPFC can be used for voltage support and transient stability improvement by damping of low frequency power system oscillations (Wang, 2000). Low frequency oscillations in electric power system occur frequently due to disturbances such as changes in loading conditions or a loss of a transmission line or a generating unit. These oscillations need to be controlled to maintain system stability. Many in the past have presented lead-lag type UPFC damping controllers (Tambey and Kothari, 2003). They are designed for a specific operating condition using linearized models. More advanced control schemes such as self-tuning control (Cheng *et al*., 1986), particle-swarm method (Al-Awami *et al*., 2007) and fuzzy logic control (Mishra *et al*., 2000; Eldamaty *et al*., 2005) offer better dynamic performances than fixed parameter controllers. Fuzzy logic UPFC damping controller is proposed here. Fuzzy control design is attractive because it does not require a mathematical model of the system under study and it can cover a wide range of operating conditions and is simple to implement.

In this study UPFC damping controller design using a fuzzy logic scheme based on the Mamdani inference engine using the center of gravity method to find the controller output is presented. The advantages of the proposed controller are their feasibility and their simplicity. The effectiveness of the controllers under dynamic conditions is illustrated through linear simulations of a SMIB power system installed with UPFC.

SYSTEM UNDER STUDY

Figure 1 shows a SMIB power system with UPFC installed (Hingorani and Gyugyi, 2000). The UPFC is installed in one of the 2 parallel transmission lines.

This configuration, comprising 2 parallel transmission lines, permits the control of real and reactive power flow through a line. The static excitation system, model type IEEE-ST1A, has been considered. The UPFC is assumed to be based on pulse width modulation (PWM) converters. The nominal loading condition and system parameters are given in Appendix 1.

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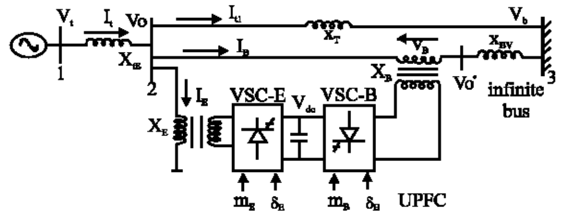

Fig. 1: A SMIB power system installed with an UPFC in one of the lines

Appendix 1: The nominal parameters and operating conditions of the system

Generator M = 8MJ/MVA	T'_{do} = 5.044 s	X_d = 1pu
X_q= 0.6 p.u.	X'_d = 0.3 pu	D = 0
Excitation system	K_a = 10	T_a = 0.05 s
	X_{tE} = 0.1pu	X_E = 0.1 pu
Transformers	X_B = 0.1 pu	
Transmission line	X_{T1} = 1 pu	X_{T2} = 1.3 pu
	P = 0.8 pu	Q = 0.15 pu
Operating condition	V_t = 1.032 pu	
DC link parameter	V'_{Dc} = 2 pu	C_{DC} = 3 pu
	m_B = 1.104	δ_B = -55.87°
UPFC parameters	δ_E = 26.9°	m_E = 1.0233

The parameter for operating point: (The operating point 1 is nominal operating point); Operating point 1: P = 0.8, Q = 0.15, Vt = 1.032; Operating point 2: P = 1, Q = 0.2, Vt = 1.032

DYNAMIC MODEL OF THE SYSTEM WITH UPFC

Non-linear dynamic model: A non-linear dynamic model of the system is derived by disregarding the resistances of all components of the system (generator, transformer, transmission lines and shunt and series converter transformers) and the transients of the transmission lines and transformers of the UPFC. The nonlinear dynamic model of the system using UPFC is given as (Tambey and Kothari, 2003):

$$\begin{cases} \dot{\omega} = \dfrac{\left(P_m - P_e - D\omega\right)}{M} \\ \dot{\delta} = \omega_0\left(\omega - 1\right) \\ \dot{E}'_q = \dfrac{\left(-E_q + E_{fd}\right)}{T'_{do}} \\ \dot{E}_{fd} = \dfrac{-E_{fd} + K_a\left(V_{ref} - V_t\right)}{T_a} \\ \dot{V}_{dc} = \dfrac{3m_E}{4C_{dc}}\left(\sin\left(\delta_E\right)I_{Ed} + \cos\left(\delta_E\right)I_{Eq}\right) \\ + \dfrac{3m_B}{4C_{dc}}\left(\sin\left(\delta_B\right)I_{Bd} + \cos\left(\delta_B\right)I_{Bq}\right) \end{cases} \tag{1}$$

The equation for real power balance between the series and shunt converters is given as Eq. (2).

$$\mathrm{Re}\left(V_B I_B^* - V_E I_E^*\right) = 0 \tag{2}$$

Linear dynamic model: A linear dynamic model is obtained by linearising the non-linear model around an operating condition. The linearised model is given:

$$\begin{cases} \Delta\dot{\delta} = \omega_0 \Delta\omega \\ \Delta\dot{\omega} = \left(-\Delta P_e - D\Delta\omega\right)/M \\ \Delta\dot{E}'_q = (-\Delta E_q + \Delta E_{fd})/T'_{do} \\ \Delta\dot{E}_{fd} = -\dfrac{1}{T_A}\Delta E_{fd} - \dfrac{K_A}{T_A}\Delta V \\ \Delta\dot{v}_{dc} = K_7\Delta\delta + K_8\Delta E'_q - K_9\Delta v_{dc} + \\ K_{ce}\Delta m_E + K_{c\delta e}\Delta\delta_E + K_{cb}\Delta m_B + K_{c\delta b}\Delta\delta_B \end{cases} \tag{3}$$

Where,

$$\begin{aligned} \Delta P_e &= K_1\Delta\delta + K_2\Delta E'_q + K_{pd}\Delta v_{dc} + K_{pe}\Delta m_E \\ &\quad + K_{p\delta e}\Delta\delta_E + K_{pb}\Delta m_B + K_{p\delta b}\Delta\delta_B \\ \Delta E_q &= K_4\Delta\delta + K_3\Delta E'_q + K_{qd}\Delta v_{dc} + K_{qe}\Delta m_E \\ &\quad + K_{q\delta e}\Delta\delta_E + K_{qb}\Delta m_B + K_{q\delta b}\Delta\delta_B \\ \Delta V_t &= K_5\Delta\delta + K_6\Delta E'_q + K_{vd}\Delta v_{dc} + K_{ve}\Delta m_E \\ &\quad + K_{v\delta e}\Delta\delta_E + K_{vb}\Delta m_B + K_{v\delta b}\Delta\delta_B \end{aligned}$$

Figure 2 shows the transfer function model of the system including UPFC. The model has 28 constants denoted by K. These constants are functions of the system parameters and the initial operating condition. The control vector u is defined as follows:

$$u = [\Delta m_E \quad \Delta\delta_E \quad \Delta m_B \quad \Delta\delta_B]^T \tag{4}$$

Where,

- Δm_B : Deviation in pulse width modulation index m_B of series inverter. By controlling m_B, the magnitude of series-injected voltage can be controlled.
- $\Delta\delta_B$: Deviation in phase angle of injected voltage.
- Δm_E : Deviation in pulse width modulation index m_E of shunt inverter. By controlling m_E, the output voltage of the shunt converter is controlled.
- $\Delta\delta_E$: Deviation in phase angle of the shunt inverter voltage.

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 power input to the series converter. The fact that the DC-voltage remains constant ensures that this equality is maintained.

It may be noted that K_{pu}, K_{qu}, K_{vu} and K_{cu} in Fig. 2 are the row vectors defined as:

$$K_{pu} = [K_{pe}\ \ K_{p\delta e}\ K_{pb}\ K_{p\delta b}];\ K_{qu} = [K_{qe}\ K_{q\delta e}\ K_{qb}\ K_{q\delta b}]$$
$$K_{vu} = [K_{ve}\ \ K_{v\delta e}\ K_{vb}\ K_{v\delta b}];\ K_{cu} = [K_{ce}\ K_{c\delta e}\ K_{cb}\ K_{c\delta b}]$$

And

$$u = [\Delta M_E\ \ \Delta\delta_E\ \ \Delta m_B\ \ \Delta\delta_B]^T$$

Dynamic model in state-space form: The dynamic model of the system in state-space from transfer-function model is as Eq. (5).

$$\begin{bmatrix} \Delta\dot{\delta} \\ \Delta\dot{\omega} \\ \Delta\dot{E}'_q \\ \Delta\dot{E}_{fd} \\ \Delta\dot{v}_{dc} \end{bmatrix} = \begin{bmatrix} 0 & w_0 & 0 & 0 & 0 \\ -\frac{K_1}{M} & 0 & -\frac{K_2}{M} & 0 & -\frac{K_{pd}}{M} \\ -\frac{K_4}{T'_{do}} & 0 & -\frac{K_3}{T'_{do}} & \frac{1}{T'_{do}} & -\frac{K_{qd}}{T'_{do}} \\ -\frac{K_A K_5}{T_A} & 0 & -\frac{K_A K_6}{T_A} & -\frac{1}{T_A} & -\frac{K_A K_{vd}}{T_A} \\ K_7 & 0 & K_8 & 0 & -K_9 \end{bmatrix} \times \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta E'_q \\ \Delta E_{fd} \\ \Delta v_{dc} \end{bmatrix}$$
$$+ \begin{bmatrix} 0 & 0 & 0 & 0 \\ -\frac{K_{pe}}{M} & -\frac{K_{p\delta e}}{M} & -\frac{K_{pb}}{M} & -\frac{K_{p\delta b}}{M} \\ -\frac{K_{qe}}{T'_{do}} & -\frac{K_{q\delta e}}{T'_{do}} & -\frac{K_{qb}}{T'_{do}} & -\frac{K_{q\delta b}}{T'_{do}} \\ -\frac{K_A K_{ve}}{T_A} & -\frac{K_A K_{v\delta e}}{T_A} & -\frac{K_A K_{vb}}{T_A} & -\frac{K_A K_{v\delta b}}{T_A} \\ Kce & K_{c\delta e} & K_{cb} & K_{c\delta b} \end{bmatrix} \times \begin{bmatrix} \Delta m_E \\ \Delta\delta_E \\ \Delta m_B \\ \Delta\delta_B \end{bmatrix} \quad (5)$$

The typical values of system parameters for nominal operation condition are given in Appendix I. The system parametric uncertainties are obtained by changing load (active and reactive power) from their typical values. Based this uncertainty, operation condition 2 is defined and shown in Appendix 1. Also a PI-type controller is considered for DC-voltage regulator in DC- link of UPFC. The parameters of this controller are given in Appendix 2.

Appendix 2: The UPFC is installed in one of the two lines of the SMIB system. The real power output of the shunt converter must be equal to the real power input of the series converter or vice versa. In order to maintain the power balance between the two converters, a DC-voltage regulator is incorporated. DC-voltage is regulated by modulating the phase angle of the shunt converter voltage. Figure A shows the structure of the DC-voltage regulator. A P-I type controller is considered for voltage regulator here. The parameters of DC-voltage regulator are considered as follow for this research.

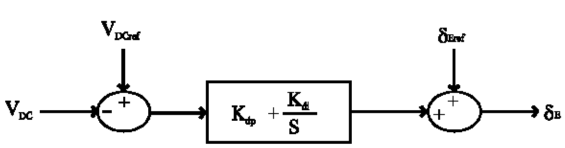

Fig. A: PI-type DC-voltage regulator

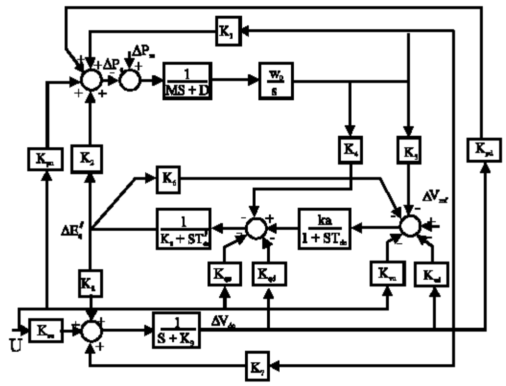

Fig. 2: Transfer function model of the system including UPFC

DAMPING CONTROLLER

A damping controller is provided to improve the damping of power system oscillations. Through damping controller an electrical torque in phase with the speed deviation is to be produced in order to improve the damping of the system oscillation. Damping controllers design themselves have been a topic of interest for decades, especially in form of power system stabilizers (PSS) and static VAR compensators (SVC) (Liou and Hsu, 1986, 1992; Smith *et al*., 1989; Zhao and Jiang, 1995; Parniani and Iravani, 1998). Different methods were used for design of damping controllers based these devices, e.g., pole-placement using lead-lag type of damping controllers, or even fuzzy logic has been used to improve transient stability. But PSS can not control of power transmission and also can not support of power system stability under large disturbances like 3-phase fault at terminals of generator (Mahran *et al*., 1992). For these problems, in this study a damping control based UPFC is provided for damping power system oscillation. Also the conventional damping controllers (like lead-lag controllers) are based on the linear control theory. The entire system model should be built first and the system is then linearized around a particular operation point. The linear controller, designed based on the linearized system, can not provide appropriate stabilization signal over a wide range of operation conditions. In turn, in this work a fuzzy logic schemes is considered for design of damping controller based UPFC. A schematic control diagram of a conventional lead-lag controller is as shown in Fig. 3. It consists of gain, signal washout and phase compensator blocks.

Fuzzy logic based UPFC damping controller: Here the proposed fuzzy supplementary controller block diagram is given in Fig. 4. In fact, this is a nonlinear PI-type fuzzy

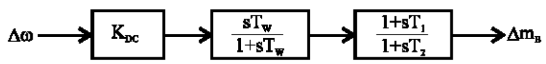

Fig. 3: Structure of classical damping controller

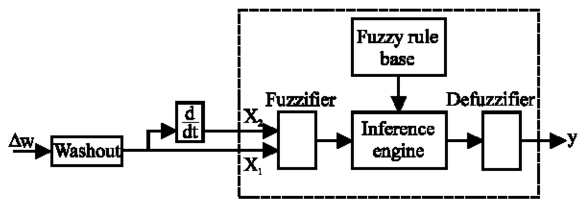

Fig. 4: Fuzzy supplementary controller

logic controller with 2 inputs and one output. The four control parameters of the UPFC (m_B, m_E, δ_B and δ_E) can be modulated in order to produce the damping torque. In this study m_B is modulated in order to output of damping controller. The speed deviation $\Delta\omega$ is considered as the input to the damping controller. The structure of fuzzy supplementary controller is shown in Fig. 4. Where, the inputs are the frequency deviation (x_1) and its rate of changes (x_2), which are filtered by washout blocks to eliminate the dc component. The output (y) is sent to the main controller for magnitude of series- injected voltage modulation.

Though the fuzzy controller accepts these inputs, it has to convert them into fuzzified inputs before the rules can be evaluated and fired. To accomplish this we have to build one of the most important and critical blocks in the whole fuzzy controllers, the knowledge base. It consists of two more blocks namely the data base and the rule base (Rajasekaran and Vijayalakshmi, 2007).

Data base: It consists of the membership function for input variables (X_1) and (X_2) described by the following linguistic variables:

For (X_1):

- Positive (P)
- Negative (N)

For (X_2):

- Negative (N)
- Near Zero (NZ)
- Positive (P)

For output variable (damping signal) described by the following linguistic variables:

- Positive (P)
- Positive Small (PS)
- Near Zero (NZ)
- Negative Small (NS)
- Negative (N)

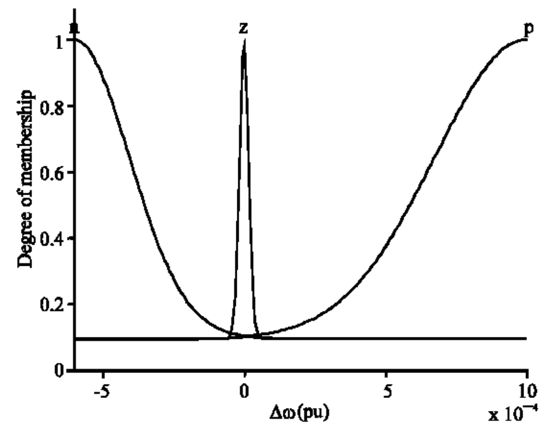

Fig. 5: Membership function of input 1 (X_1)

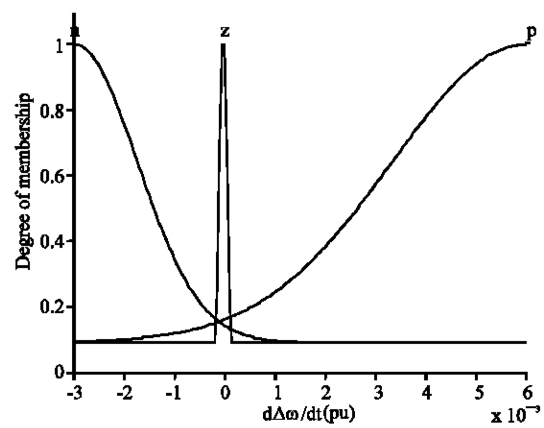

Fig. 6: Membership function of input 2 (X_2)

The "Gaussian membership functions" are used as membership functions for the input variables and "triangular membership functions" for output variable (Rajasekaran and Vijayalakshmi, 2007). Figure 5-7 illustrate these in detail, indicating the range of all the variables.

Rule base: The other half of the knowledge base is the rule base, which consists of, all the rules formulated by the experts. It also consists of weights, which indicate the relative importance of the rules among themselves and indicates the influence of a particular rule over the net fuzzified output. The fuzzy rules used in our scheme are as mentioned below in the Table 1. The next section specifies the method adopted by the inference engine, especially the way it uses the knowledge base consisting of the described data base and rules base (Rajasekaran and Vijayalakshmi, 2007). Plot of inputs versus output, based rules base, is shown in Fig. 8.

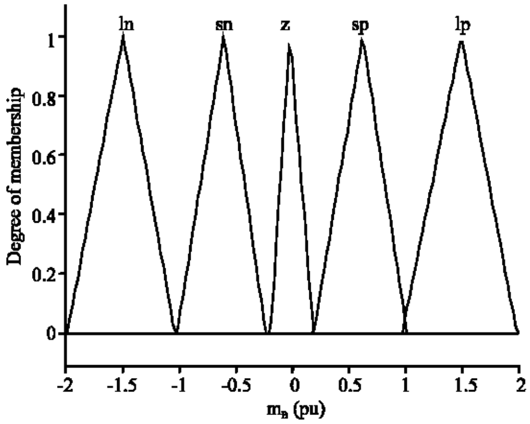

Fig. 7: Membership function of output

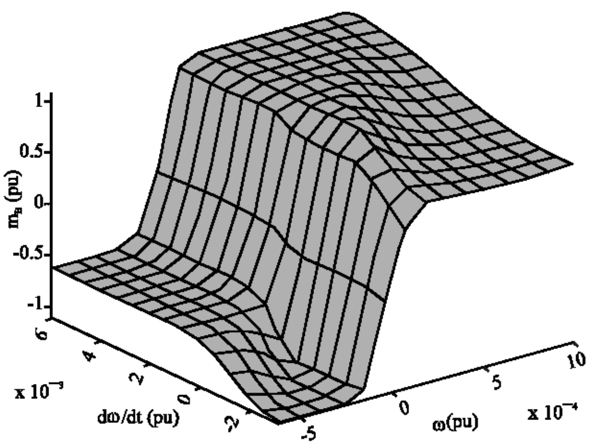

Fig. 8: Output coefficients versus two inputs

Table 1: Fuzzy rules

Rule 1: If (X_2) is NZ then (y) is NZ (1)
Rule 2: If (X_2) is P then (y) is P (1)
Rule 3: If (X_2) is N then (y) is N (1)
Rule 4: If (X_2) is NZ and (X_1) is P then is NS
Rule 5: If (X_2) is NZ and (X_1) is N then is PS

Methodologies adopted in fuzzy inference engine: Though we have mentioned many methodologies in evaluating the various expressions like fuzzy union (OR operation), fuzzy intersection (AND operation), etc, with varying degree of complexity, we in our fuzzy scheme use the most widely used methods for evaluating such expressions. The function used for evaluating OR is "MAX", which is nothing but the maximum of the 2 operands, i.e.,

$$\begin{aligned} \text{MAX}(X1, X2) &= X1 \text{ if } X1 > X2 \\ &= X2 \text{ if } X1 < X2 \end{aligned}$$

Similarly, the AND is evaluated using "MIN" function which is defined as the minimum of the two operands, i.e.,

$$\begin{aligned} \text{MIN}(X1, X2) &= X1 \text{ if } X1 < X2 \\ &= X2 \text{ if } X1 > X2 \end{aligned}$$

Another important point to note here is that in the present research paper, we have assigned equal importance to all the rules in the rules base, i.e., all the weights are equal and this is indicated in the fuzzy rules Table 1 in the parenthesis against each rule (Rajasekaran and Vijayalakshmi, 2007).

De-fuzzification method: The de-fuzzification method followed in our study is the "center of area method" or "gravity method". This method is discussed in Rajasekaran and Vijayalakshmi (2007).

ANALYSIS AND SIMULATION RESULTS

For nominal operating condition, the eigen-values of the system are obtained (Table 2) usage state-space from transfer-function model of system in Eq. (5) and it is clearly seen that the system is unstable.

Design of damping controller for stability: The fuzzy control design approach presented in previous section is now applied to design of damping controller in test system. To show effectiveness of fuzzy method, a classic lead-lag damping controller is designed. The parameters of the classic damping controller are obtained using the phase compensation technique. The detailed step-by-step procedure for computing the parameters of the damping controllers using phase compensation technique is presented in Yu (1983) and Wang *et al.* (1997).

The four control parameters of the UPFC (m_B, m_E, δ_B and δ_E) can be modulated in order to produce the damping torque. In this study m_B is modulated in order to classic damping controller design. The speed deviation $\Delta\omega$ is considered as the input to the damping controllers. Classic damping controllers was designed and obtained as follows (wash-out block is considered). Damping controller of power flow controller with damping ratio of 0.5 is:

$$\text{Damping controller} = \frac{536.0145 \quad s \quad (s+3.656)}{(s+0.1) \quad (s+4.5)}$$

After employ this damping controller to system, the eigen-values of the system with damping controller are obtained (Table 3) and it is clearly seen that the system is stable.

Table 2: Eigen-values of the closed-loop system without damping controller

-19.2516
0.0308±2.8557i
-0.6695±0.5120i

Table 3: Eigen- values of the closed-loop system with damping controller

-19.3328, -16.4275, -2.8609
-0.9251±0.9653i
-0.8814, -0.1067

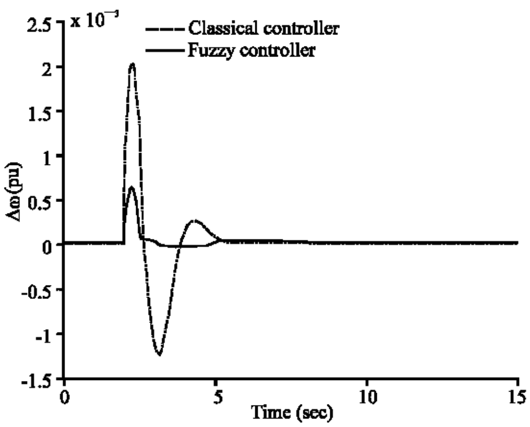

Fig. 9: Speed deviation for case 1

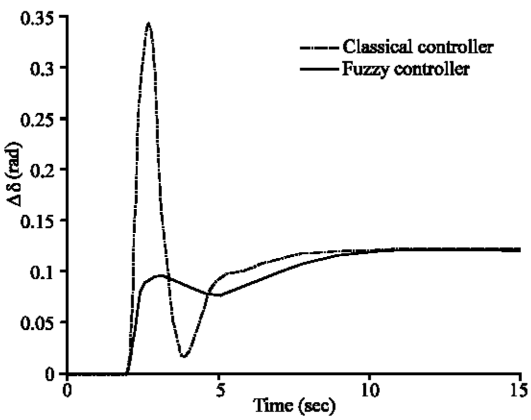

Fig. 10: Rotor angle deviation for case 1

The results obtained with the fuzzy damping controller are compared to those obtained with the lead-lag controller applied to the series converter side. In this section two cases are simulated, case 1: nominal operation condition and case 2: heavy operation condition. Both, fuzzy and lead-lag damping controllers were designed for the nominal operating condition. The simulation result depicted in Fig. 9 and 10 shows that adding the supplementary control signal greatly enhances the damping of the generator angle oscillations and therefore the system becomes more stable. The fuzzy controller performs better than the conventional controller. Also,

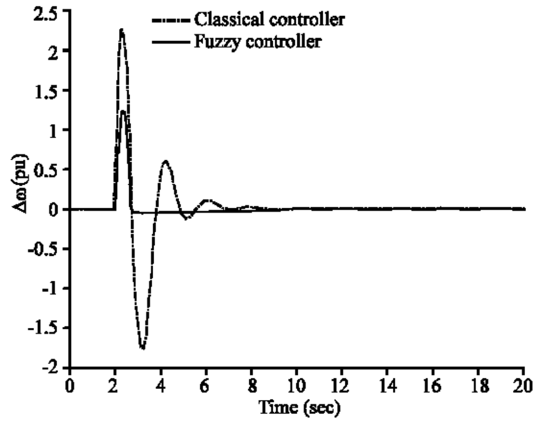

Fig. 11: Speed deviation for case 2

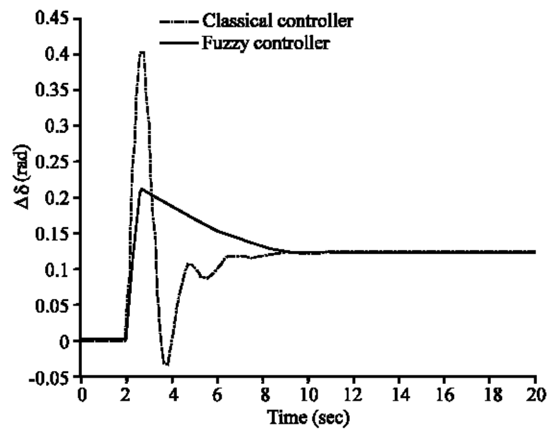

Fig. 12: Rotor angle deviation for case 2

both damping controllers were designed for case 2. The simulation results are shown in Fig. 11 and 12. Under this condition, while the performance of classic supplementary controller becomes poor, the fuzzy controller has a good and robust performance. We can conclude the fuzzy supplementary controller have good parameter adaptation in comparison with the classic supplementary controller when operation condition changes. Simulations are carried out in MATLAB (2006).

CONCLUSION

In this study a fuzzy supplementary damping controller is designed for UPFC. Design strategy includes enough flexibility to setting the desired level of stability and performance and considering the practical constraint by introducing appropriate uncertainties. The proposed method was applied to a typical SIMB power system installed with an UPFC with various loads conditions. Simulation results demonstrated that the designed controller capable to guarantee the robust stability and robust performance under a various load conditions. Also, linear simulation results show that the proposed method has an excellent capability in damping of power system oscillations and enhance of power system stability under small disturbances in compare to classical method.

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