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Fuzzy Based Controller for Damping of Inter-Area Oscillations Using UPFC

M. Sreedevi and P. Jenopaul
Department of Electrical and Electronics Engineering,
Anna University of Technology, Chennai, Tamil Nadu, India

Abstract: The Unified Power Flow Controller (UPFC) is the one of the FACTS devices which can control power system parameters such as terminal voltage, line impedance and phase angle. The UPFC is not only power flow controller but also power system stabilizing controller. The 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. UPFC is the one FACTS device which can control real and reactive power flow. UPFC can control the power system parameters such as terminal voltage, line impedance and phase angle. UPFC control provides additional damping during oscillations. The dynamic models of UPFC are used to design suitable controllers for power flow, voltage and damping controls. Fuzzy logic controller based UPFC is taken in this research. The parameters of UPFC (m_B, m_E, δ_B and δ_e) can be modulated for achieving desired damping in the system. The performance of the four UPFC based damping controllers (m_B, m_E, δ_B and δ_E) and fuzzy based controllers are investigated under wide variations of the loading conditions in this research. A Single-Machine-Infinite-Bus (SMIB) system installed with UPFC is considered. The static excitation system model type IEEE-ST1A has been considered in this study. The UPFC considered here is assumed to be based on Pulse Width Modulation (PWM) converters.

Key words: SMIB, UPFC, fuzzy logic controller, design, power system, India

INTRODUCTION

UPFC is the one FACTS device which can control real and reactive power flow. UPFC can control the power system parameters such as terminal voltage, line impedance and phase angle. UPFC control provides additional damping during oscillations.

The dynamic models of UPFC are used to design suitable controllers for power flow, voltage and damping controls (Nabavi-Niaki and Iravani, 1996; Smith *et al*., 1997; Makombe and Jenkins, 1999; Papic *et al*., 1997; Morioka *et al*., 1999; Wang, 1999). Modified Linearised Heffron-Phillips model of a power system installed with UPFC is taken in this research fuzzy logic controller.

The parameters of UPFC (m_B, m_E, δ_B and δ_E) can be modulated for achieving desired damping in the system. The performance of the four UPFC based damping controllers (m_B, m_E, δ_B and δ_E) are investigated under wide variations of the loading conditions in this research.

MATERIALS AND METHODS

System investigated: A Single-Machine-Infinite-Bus (SMIB) system installed with UPFC is considered as shown in Fig. 1. The static excitation system model type IEEE-ST1A has been considered in this research. The

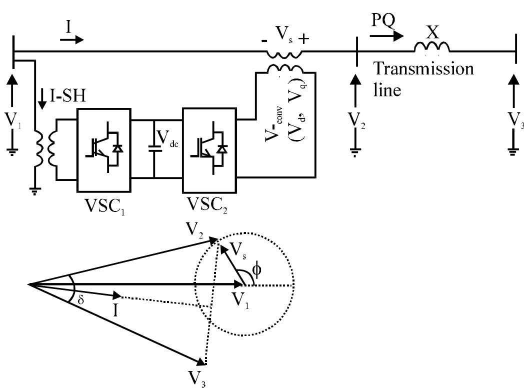

Fig. 1: UPFC installed in a SMIB system

Corresponding Author: M. Sreedevi, Department of Electrical and Electronics Engineering, Anna University of Technology, Chennai, Tamil Nadu, India

UPFC considered here is assumed to be based on Pulse Width Modulation (PWM) converters. The nominal loading condition and system parameters are given:

Generator:

$$M = 2H = 8.0 \text{ MJ/MVA}, D = 0.0$$
$$T_{do} = 5.044 \text{ sec}, X_d = 1.0 \text{ p.u.}$$
$$X_q = 0.6 \text{ p.u.}, X_d = 0.3 \text{ p.u.}$$

Excitation system:

$$K_a = 100, T_a = 0.01 \text{ sec}$$

Transformers:

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

Transmission line:

$$X_{BV} = 0.3 \text{ p.u.}$$

$$X_E = X_{BV}+X_B+X_{tE} = 0.5 \text{ p.u.}$$

Operating condition:

$$P_e = 0.8 \text{ p.u.}, V_t = 1.0 \text{ p.u.}$$

$$V_b = 1.0 \text{ p.u., Frequency} = 60 \text{ Hz}$$

UPFC parameters:

$$m_E = 0.4013, \quad m_B = 0.078$$

$$\delta_E = -85.3478, \quad \delta_B = -782174$$

DC link parameters:

$$V_{dc} = 2 \text{ p.u.}, C_{dc} = 1.0 \text{ p.u.}$$

Modified Heffron-Phillips small perturbation transfer function model of a SMIB system including UPFC: The small perturbation transfer function block diagram of a machine-infinite bus system including UPFC relating the pertinent variables of electric torque, speed, angle, terminal voltage, field voltage, flux linkages, UPFC control parameters and dc link voltage is used in this research as shown in Fig. 2. This model has been obtained (Wang, 1999, 2000) by modifying the basic Heffron-Phillips model including UPFC. In Fig. 2, Δu is the column vector while $[K_{pu}]$, $[K_{qu}]$, $[K_{vu}]$ and $[K_{cu}]$ are the row vectors as defined:

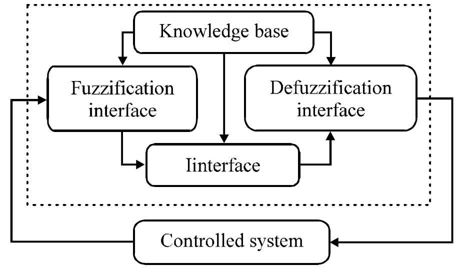

Fig. 2: FLC building blocks

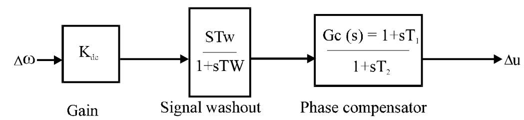

Fig. 3: Structure of UPFC based damping controllers

$$[\Delta u] = [\Delta m_E \quad \Delta\delta_E \quad \Delta m_B \quad \Delta\delta_B]^T$$
$$K_{pu} = [K_{pe} \quad K_{p\delta e} \quad K_{pb} \quad K_{P\delta b}]$$
$$K_{qu} = [K_{qe} \quad K_{q\delta e} \quad K_{qb} \quad K_{q\delta b}]$$
$$K_{vu} = [K_{ve} \quad K_{v\delta e} \quad K_{vb} \quad K_{v\delta b}]$$
$$K_{cu} = [K_{ce} \quad K_{c\delta e} \quad K_{cb} \quad K_{c\delta b}]$$

The control parameters of UPFC are:

- In m_B-Modulating index of series inverter by controlling m_B, the magnitude of series injected voltage can be controlled, thereby controlling the reactive power compensation
- δ_B-Phase angle of series inverter which controlled results in the real power exchange
- In m_E-Modulating index of shunt inverter by controlling m_E, the voltage at a bus where UPFC is installed is controlled through reactive power compensation
- δ_B Phase angle of the shunt inverter which regulates

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 (m_B, m_E, δ_B and δ_E) 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 alternative UPFC based damping controllers are examined in this research (Table 1).

The structure of UPFC based damping controller is shown in Fig. 3. It consists of gain, signalwashout and phase compensator blocks.

Table 1: Eigen values of the closed loop system

Eigen-values	ω_n of oscillatory mode	ζ of the oscillatory modes
System without any damping controller		
-19.1186	4.09 rad sec^{-1}	-0.00297
0.0122±4.0935i		
-1.2026		

Table 2: Parameters of the UPFC based damping controllers

Parameters	K_{dc}	T_1	T_2
Damping controller (m_E)	14.8813	0.3383	0.1761
Damping controller (δ_E)	18.0960	0.2296	0.2516
Damping controller (m_B)	41.1419	0.2860	0.2082
Damping controller (δ_B)	382.4410	0.2266	0.2694

Structure of UPFC base damping controllers: The parameters of the damping controller are obtained using the phase compensation technique (Gyugyi, 1992) (Table 2). The phase compensation technique is used to find out the damping control parameters. The detailed step-by-step procedure for computing the parameters is given as:

- Computation of natural frequency of oscillation ω_n from the mechanical loop:

$$\omega_n = \sqrt{\frac{K_1\omega_0}{M}}$$

- Computation of GEPA (phase lag between Δu and ΔP_e) at $s = j\omega_n$. Let it be γ
- Design of phase lead/lag compensator Gc

The phase lead/lag compensator Gc is designed to provide the required degree of phase compensation. For 100% phase compensation:

$$Gc\,(j\omega_n) + GEPA\,(j\omega_n) = 0$$

Assuming one lead-lag network $T_1 = aT_2$; the transfer function of the phase compensator becomes:

$$Gc(s) = \frac{1 + saT_2}{1 + sT_2}$$

Since, the phase angle compensated by the lead-lag network is equal to $-\gamma$, the parameters a and T_2 are computed as:

$$a = \frac{1+\sin\gamma}{1-\sin\gamma};\quad T_2 = \frac{1}{\omega_n\sqrt{a}}$$

Computation of optimum gain K_{dc}. The required gain setting K_{dc} for the desired value of damping ratio $\zeta = 0.5$ is obtained as:

Table 3: Gain and phase angle of the transfer function GEPA

GEPA	|GEPA|	∠GEPA
$\Delta P_e/\Delta m_E$	1.5891	-18.3805°
$\Delta P_e/\Delta \delta_E$	1.9251	3.4836°
$\Delta P_e/\Delta m_B$	0.6789	-9.0527°
$\Delta P_e/\Delta \delta_B$	0.0923	4.257°

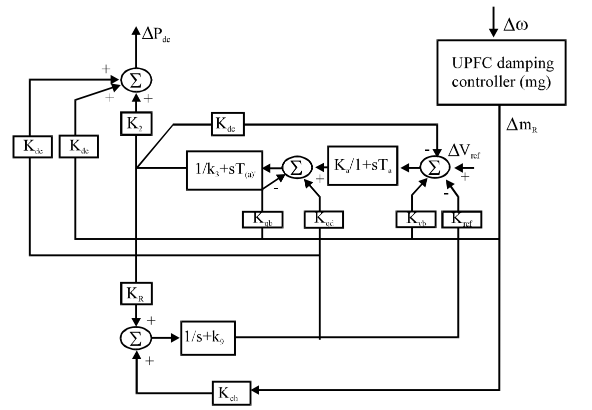

Fig. 4: Transfer function of the system-relating component of Electrical power (ΔP_e) produced by the damping controllers

$$K_{dc} = \frac{2\zeta\omega_n M}{|Gc(s)||GEPA(s)|}$$

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 parameter. The value of the washout time constant T_w should be high enough to allow signals associated with oscillations in rotor speed to pass unchanged.

From the viewpoint of the washout function, the value of T_w is not critical and may be in the range of 1-20 sec. T_w is equal to 10 sec is chosen in the present research.

Figure 4 shows the transfer function of the system relating the electrical component of the power produced by the damping controller (m_B). The time constants of the phase compensator are chosen so that the phase lag/lead of the system is fully compensated. For the nominal operating condition, the natural frequency of oscillation ω_n = 4.0974 rad sec^{-1}.

The transfer function relating ΔP and Δm_B is denoted as GEPA. For the nominal operating condition, phase angle of GEPA, ∠GEPA = 9.057° lagging. The manitude of GEPA, |GEPA| = 0.6798. To compensate the phase lag, the time constants of the lead compensator are obtained as T_1 = 0.2860 and T_2 = 0.2082 sec (Table 3).

Fuzzy logic controller: In the conventional control, the amount of control is determined in relation to a number of data inputs using a set of equations to express the entire control process. Expressing human experience in the form of a mathematical formula is a very difficult task if not an impossible one.

Fuzzy logic provides a simple tool to interpret this experience into reality. Fuzzy Logic Controllers (FLC) are rule-based controllers. The structure of the FLC resembles that of a knowledge based controller except that the FLC utilizes the principles of the fuzzy set theory in its data representation and its logic. The basic configuration of the FLC can be simply represented in four parts as shown in Fig. 2.

Fuzzification module: The functions of which are 1st to read, measure and scale the control variable (speed, acceleration) and 2nd to transform the measured numerical values to the corresponding linguistic (fuzzy variables with appropriate membership values).

Knowledge base: This includes the definitions of the fuzzy membership functions defined for each control variables and the necessary rules that specify the control goals using linguistic variables.

Inference mechanism: It should be capable of simulating human decision making and influencing the control actions based on fuzzy logic. In the inference mechanism, rules are defined by the user. On the bases of these rules, output of fuzzy controller is controlled.

Defuzzification module: Which converts the inferred decision from the linguistic variables back the numerical values.

The 1st step in designing a fuzzy controller is to decide which state variables represent of system dynamic performance must be taken as the input signal to the controller.

However, choosing the proper linguistic variables formulating, the fuzzy control rules are very important factors in the performance of the fuzzy control system. System variables which are usually used as the fuzzy controller inputs includes states error state error derivative, state error integral, etc.

In power system, based on previous experience. Generator speed deviation ($\Delta\omega$) and acceleration ($\Delta\omega$) are chosen to be the input signals of fuzzy PSS. As it was mentioned earlier if the synchronous generator automatic voltage regulator is utilized in a proper way, it is capable of damping electromechanically oscillations of the generator shaft. The input to the excitation system would be the control variable which is actually the output of fuzzy PSS.

In practice, only shaft speed deviation is ready available. Hence, the acceleration signal can be derived from speed signals measured at two sampling instant by the following expression:

$$\Delta\omega(kT_s) = \frac{\Delta\omega(kT_s) - \Delta\omega((k-1)T_s)}{T_s}$$

where, T_s is the sampling time. Universe of discourse which is basically the range of input variable is selected from -3 to 3 for present investigation. For best result, the UOD should be minimum but greater then input of fuzzy controller. Fuzzification of crisp input signals menace conversion of numerical input signal from SMIB system into fuzzy logic form.

After choosing proper variables as input and output of fuzzy controller, it is required to decide the membership function (mfs). These variables transform the numerical values of the input of the fuzzy controller to fuzzy quantities. The number of these membership function specifies the quality of the control which can be achieved using the fuzzy controller. As the number of the membership function increases, the computational time and required memory increase.

Therefore, a compromise between the quality of control and computational time is needed to choose the number of linguistic variables. For the power system under study, five membership function for each of the input and output variables are used to describe them as in the following Table 4.

The performance of a FLC also depends upon the type of membership functions. The most commonly used membership functions are triangular, trapezoidal and Gaussian. All the investigations are carried out considering Gaussian membership functions. A Gaussian membership function is defined as:

$$f(X, \sigma, C) = \frac{e^{-(X-C)^2}}{2\sigma^2}$$

Table 4: Input and output membership function

Input	Output
NB	Negative big
NS	Negative small
Z	Zero
PS	Positive small
PB	Positive big

Table 5: Rule base with five membership functions

	$\Delta\omega$				
$\Delta\dot{\omega}$	NB	NS	ZO	PS	PB
NB	NB	NB	NB	NS	ZO
NS	NB	NS	NS	ZO	NS
ZO	NB	NS	ZO	PS	PB
PS	NS	ZO	PS	PS	PB
PB	ZO	PS	PB	PB	PB

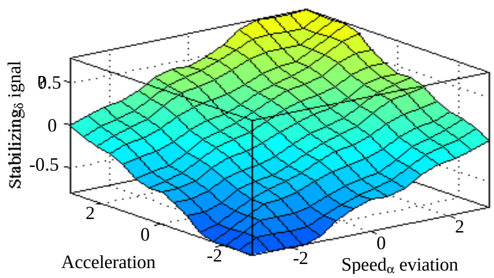

Fig. 5: Surface view of stabilizing signal according to both inputs (speed deviation and acceleration)

Where:

c = Center of Gaussian membership function

σ^2 = Variance

For the present investigations $\sigma = 1.75$ is chosen and all the membership functions are symmetrically placed in the Universe of Discourse (UOD) from -3 to 3. Mamdani inference engine is used. The two inputs; speed deviation and acceleration, result in 25 rules for each machine.As shown in Table 5 that results of 25 rules where a positive control signal is for the deceleration control and a negative signal is for acceleration control. After it, the next step is aefuzzification in which the stabilizer output which is in fuzzy form is to be converted in numeric values. On the bases of these rules the FLC output in the form of stabilizing signal can seen on surface viewer as shown in Fig. 5.

RESULTS AND DISCUSSION

The Heffron-Philips model of a SMIB with UPFC has been simulated using Matlab-Simulink software with estimated K constant values. In this research for the improvement of the SMIB system, we have introduced a fuzzy based damping controller with the UPFC (Fig. 6 and 7). Here, response of the SMIB system are analysed with and without UPFC based damping controllers for various configurations (Fig. 8a, b). Dynamic responses for the alternative damping controllers the different values of X_e at P_e = 0.8 p.u. Q_e = 0.1670 p.u. are given:

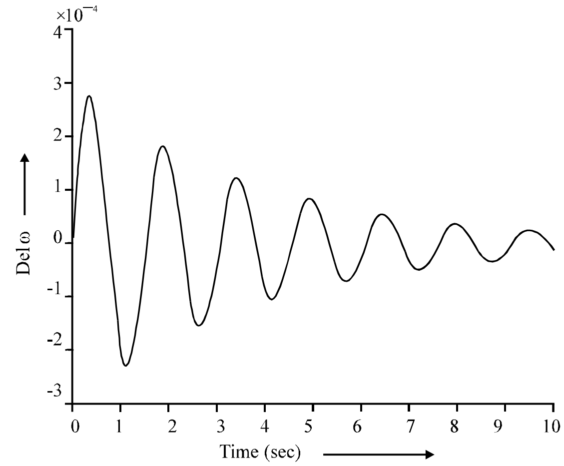

Fig. 6: Without UPFC based damping controller

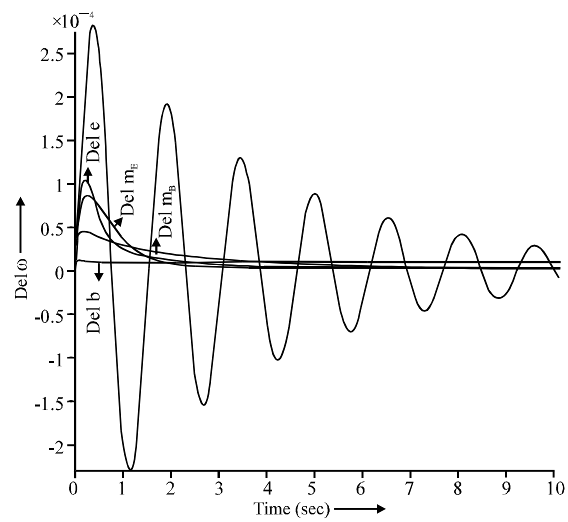

Fig. 7: Combined dynamic responses for $\Delta\omega$ with and without UPFC based damping controller

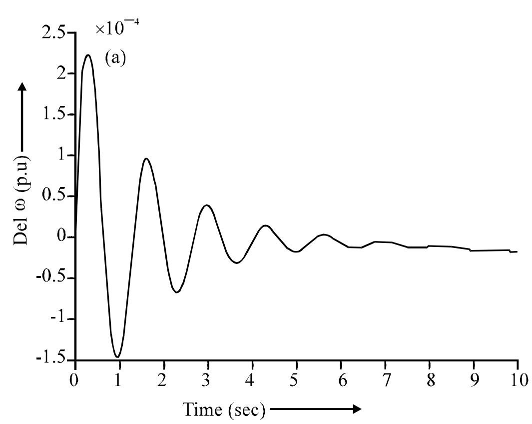

Fig. 8: Continue

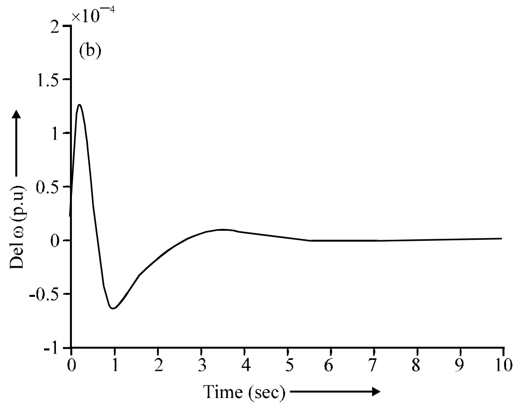

Fig. 8: An introduction of fuzzy based damping controller

Damping controller (δ_B):

$$X_e = 0.65 \text{ p.u.}, X_{BV} = 0.45 \text{ p.u.}$$

Fuzzy based damping controller:

$$X_e = 0.3 \text{ p.u.}, X_{VB}=0.1 \text{ p.u.}$$

CONCLUSION

The present research has been directed towards developments of UPFC based damping controllers for power system stabilization. The modified Heffron-Phillips model of SMIB power system installed with fuzzy based damping controlled UPFC is taken in the present research. The alternative UPFC based damping controllers for damping power system oscillations also has been examined in this research.

The modified Heffron-Phillips model of SMIB power system installed with UPFC and without UPFC is simulated using Matlab-Simulink. The performance of the four alternative damping controllers (m_B, m_E, δ_B and δ_E) has been examined considering wide variations in loading conditions and line reactance X_n in this work. Investigations reveal that the damping controller (δ_B) and damping controller (δ_E) provide robust performance to wide variations in loading conditions and line reactanceX_e. The simulation results shows that the fuzzy based damping controllers on UPFC control parameters may be preferred over the existing damping controllers.

NOMENCLATURE

C_{dc} = dc link capacitance
D = Damping constant
H = Inertia constant (M = 2H)
K_a = AVR gain
K_{dc} = Gain of damping controller
m_B = Modulation index of series converter
m_E = Modulation index of shunt converter
P_e = Electrical power of the generator
P_m = Mechanical power input to the generator
T_a = Time constant of AVR
T_{do} = d-axis open circuit time-constant of generator
T_1, T_2 = Time constants of phase compensator
V_b = Infinite bus voltage
V_{dc} = Voltage at dc link
V_t = Terminal voltage of the generator
X_B = Reactance of boosting transformer (BT)
X_{Bv} = Reactance of the transmission line
X_d = Direct axis steady-state synchronous reactance of generator
X'_d = Direct axis transient synchronous reactance of generator
X_E = Reactance of excitation transformer (ET)
X_e = Equivalent reactance of the system
X_q = Quadrature axis steady-state synchronous reactance of generator
X_{tE} = Reactance of transformer
δ_B = Phase angle of series converter voltage
δ_E = Phase angle of shunt converter voltage
ω_n = Natural frequency of oscillation (rad sec^{-1})

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