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UNIFIED POWER FLOW CONTROL IN THE PRESENCE OF PSS WITH FUZZY CONTROLLER FOR A MULTI-MACHINE SYSTEM

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Abstract: This paper presents a comprehensive approach for the design of UPFC controllers (i.e. power flow controller, DC voltage regulator and damping controller) for a multimachine system. UPFC controllers have been designed in the presence of conventional PSS. The interaction between the UPFC controllers and PSS has been studied. Investigations reveal that the system damping gets adversely affected with the incorporation of DC voltage regulator. Investigations have been carried out to understand relative effectiveness of modulation of the UPFC control signals (mB, δB, mE and δE) on damping of the system oscillations using controllability index. Studies reveal that the UPFC based damping controller considering modulation of control parameter mB is most effective in damping the oscillations.

Keywords: FACTS, Optimization, Power system Stability, UPFC

I. INTRODUCTION

The Unified Power Flow Controller (UPFC) is a Flexible AC Transmission System (FACTS) device using a Voltage Sourced Converter (VSC), which is based on Gate-Turn-Off (GTO) thyristor valve technology. It may be viewed as a coordinated combination of a Static Synchronous Compensator (STATCOM) and a Static Synchronous Series Compensator (SSSC), which utilize the same technology, coupled via a common dc link. The UPFC has been devised for real time control and dynamic compensation of the ac transmission systems, providing multifunctional flexibility required for solving many of the complex problems facing the power delivery industry. The ability of the UPFC to control concurrently or selectively, the transmission line voltage, impedance and angle, makes it the most versatile FACTS device. The primary function of UPFC is to control power flow on a given line and voltage at the UPFC bus. The UPFC can also be effectively used for damping power system oscillations by judiciously applying a damping controller. For an UPFC based damping controller, it is desired to extract an input signal to the damping controller from locally measurable quantities at the UPFC location. The power flow on the line can be easily measured at the UPFC location and hence may be used as an input signal to the damping controller.

Recently steady-state and dynamic models of UPFC have been developed by several researchers [1-5]. Nabavi-Niaki and Iravani [1] have presented comprehensive mathematical models of UPFC for steady-state, transient stability and dynamic stability studies. Makombe and Jenkins [2] have derived the mathematical model of a vector controlled UPFC. Morioka et al [3] have described control and protection schemes for UPFC operation. The UPFC miniature model has been developed and verified using a power system simulator. Smith et al [4] have developed decoupled control algorithms of the three independent compensation variables (i.e. real component of series injected voltage, reactive component of series injected voltage and reactive current of shunt converter) of the UPFC. They have developed the analytical models of the system with UPFC for both transient and dynamic performance studies. Papic et al [5] have presented the basic control system, which enables the UPFC to follow the changes in reference values of the active and reactive power supplied from the external system controller. Padiyar and Kulkarni [6] have proposed an UPFC control strategy based on local measurements, in which real power flow through the line is controlled by reactive voltage injection and the reactive power flow is controlled by regulating the magnitude of voltages at the two ports of the UPFC. They have also included an auxiliary controller for improving the transient stability of the system. Wang [7-9] has developed linearised models of the power system installed with UPFC. These models are known as Modified Heffron-Phillips models. Tambey and Kothari [10] have presented a comprehensive approach for the design of UPFC controllers for a SMIB system.

A brief review of the literature shows that a lot of research work pertaining to the application of UPFC has been reported during a last one decade. The attention of the researchers has been focused on development of dynamic models and control strategies. Hardly any effort seems to have been made to optimize the UPFC controllers for a mulltimachine system. Moreover, studies have not been carried out to understand interaction of the UPFC controllers with existing power system stabilizers (PSS). In view of the above, the main objectives of the research work presented in the paper are as follows:

1. To present a systematic approach for optimum location of PSS in a multimachine system and hence to optimize the parameters of PSS.
2. To present a comprehensive approach for designing UPFC controllers (i.e. power flow controller, DC voltage regulator and damping controller) for a multimachine system.
3. To investigate the dynamic interaction between UPFC controllers and PSS.

II. SYSTEM INVESTIGATED

A 3-machine, 9-bus system [11] has been considered (Fig. 1). The system data as given in ref.[11] have been used. The static excitation system model type IEEE-ST1A has been considered for all the three generators. UPFC is based on pulse width modulation (PWM) voltage-sourced converters The UPFC is installed on line 7-8 for controlling power flow on the line.

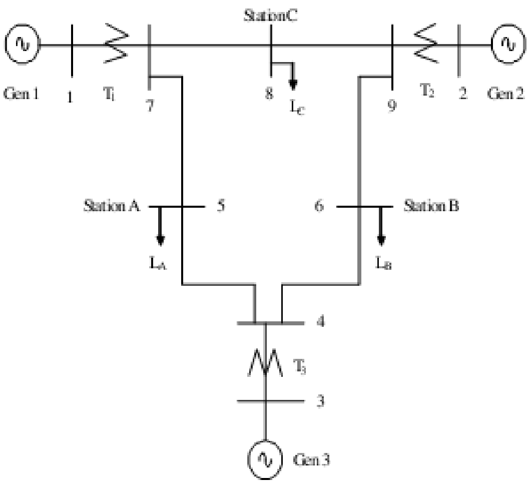

Fig 1: WSSC 3-machine, 9bus system

III. DYNAMIC MODEL WITH UPFC

A. Nonlinear Dynamic Model

For developing the dynamic model of the system, the network is represented by taking out the buses connecting the line in which UPFC is installed. These buses are numbered as buses 1 and 2 (Fig. 2). UPFC consists of shunt and series converters connected back to back through a dc link. The two GTO based converters (VSCs) are coupled to the system through excitation and boosting transformers. The modulation ratio and phase angle control signals of shunt converter are denoted by mE and δE. Similarly the modulation ratio and phase angle control signals of series converter are denoted as mB and δB. The resistances of the transformers are neglected.While developing the model, the transients associated with the transformers are ignored.

The nonlinear model of a multimachine system with UPFC as developed by Wang [9] is given below:

$$\dot{\delta} = \omega_O(\omega - I) \quad \cdots (1)$$

$$\dot{\omega} = M^{-1}(P_M - P_e - D\Delta\omega) \quad \cdots (2)$$

$$\dot{E_q'} = T'^{-1}_{do}\left((X_D - X'_D)I_D - E'_q + E_{fd}\right) \cdots (3)$$

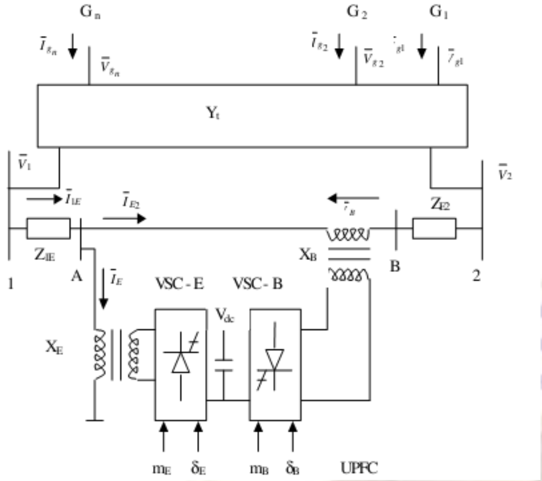

Fig 2: n-machine power system with UPFC installed

$$\dot{E_{fd}} = -T_A^{-1}E_{fd} + T_A^{-1}K_A\left(V_{ref} - V_T\right) \cdots (4)$$

$$\dot{V_{dc}} = \frac{3m_E}{4C_{dc}}(\cos\delta_E I_{Ed} + \sin\delta_E I_{Eq})$$

$$+\frac{3m_B}{4C_{dc}}(\cos\delta_B I_{Bd} + \sin\delta_B I_{Bq}) \cdots(5)$$

Where, $P_e = V_{TD}I_d + V_{TQ}I_q$, $V_{TD} = X_Q I_q$

$$V_{TQ} = E'_q - X'_D I_d \quad , \quad V_{Ti} = \sqrt{V_{TDi}^2 + V_{TQi}^2}$$

$$\omega = [\omega_1 \;\; \omega_2 \cdots \omega_n]^T$$
$$E'_q = \left[E'_{q1} \;\; E'_{q2} \cdots E'_{qn}\right]^T$$

$$E_{fd} = [E_{fd1} \;\; E_{fd2} \cdots E_{fdn}]^T$$

$$I_d = [I_{d1} \;\; I_{d2} \cdots I_{dn}]^T \;\; , \;\; I_q = \left[I_{q1} \;\; I_{q2} \cdots I_{qn}\right]^T$$

$$V_{TD} = [V_{d1} \;\; V_{d2} \cdots V_{dn}]^T \; V_{TQ} = \left[V_{q1} \;\; V_{q2} \cdots V_{qn}\right]^T$$

$M = diag(2H_i)$, $D = diag(D_i)$
$T'_{do} = diag(T'_{doi})$, $X_D = diag(X_{di})$

$X_Q = diag\left(X_{qi}\right)$, $X'_D = diag(X'_{di})$

i = 1, 2, ⋯n, n is number of generators

B. Linear Dynamic Model in State Space Form

The linear dynamic model in state space form (Eqn. (6)) is obtained by linearising the non-linear model around a nominal operating condition.

$$\dot{X} = AX + Bu + \Gamma p \cdots (6)$$

Where,

$$X = \left[\Delta\delta^T \;\; \Delta\omega^T \;\; \Delta E_q'^T \;\; \Delta E_{fd}^T \;\; \Delta V_{dc}\right]^T$$

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

p is the perturbation vector. **A**, **B** and Γ are the compatible matrices and are function of system parameters and operating condition.

C. Modified Heffron-Phillips Transfer Model of a Multimachine system with UPFC

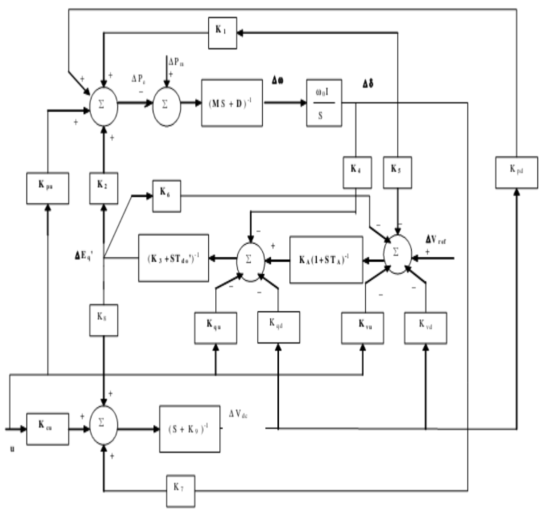

Fig 3: Linearised Modified Heffron-Phillips model of n-machine system with UPFC installed

Fig. 3 shows the transfer function model of a multimachine system including UPFC. In this model, Δδ, Δω, ΔE'q, ΔEfd and ΔVT are all n dimensional vectors. K1 - K6 are n×n matrices. Kpu, Kqu, Kvu and Kcu are defined as :

Kpu=[Kpe Kpδe Kpb Kpδb]

Kqu=[Kqe Kqδe Kqb Kqδb]

Kvu=[Kve Kvδe Kvb Kvδb]

Kcu=[Kce Kcδe Kcb Kcδb]

Where, **Kpu**, **Kqu** and **Kvu** are n×4 matrices. **Kcu** is a row vector. **Kpe**, **Kpδe**, **Kpb**, **Kpδb**, **Kqe**, **Kqδe,** **Kqb**, **Kqδb**, Kve, **Kvδe**, **Kvb** and **Kvδb** are n dimensional column vectors. All the constants of the model are functions of the system parameters and operating condition.

F.FUZZY LOGIC

In 1965, Zadeh proposed Fuzzy logic; it has been effectively utilized in many field of knowledge to solve such control and optimization problems [15]. FLC is a good mean to control the parameters when there isn't any direct and exact relation between input and output of the system, and we only have some linguistic relations in the If-Then form [16]. The use of fuzzy logic has received increased attention in recent years because of its usefulness in reducing the need for complex mathematical models in problem solving [17]. In power system area, it has been used to stability studies, load frequency control, unit commitment, and to reactive compensation in distribution network and other areas. Fuzzy control system is made from different blocks such as numeral quantity converter to fuzzy quantities (fuzzifier interface) block, the fuzzy logical decision maker section, knowledge base section, and defuzzier interface block.

The following steps are involved in designing the fuzzy UPFC controller [18]:

1) Choose the inputs to the FLC. As shown in Fig. 3, only two inputs, the generator speed deviation (ΔΨ) and generator speed derivative deviation (Δ), have been employed in this study. The symbol U_c has been synonymously used to represent the output or decision variable of FLC.

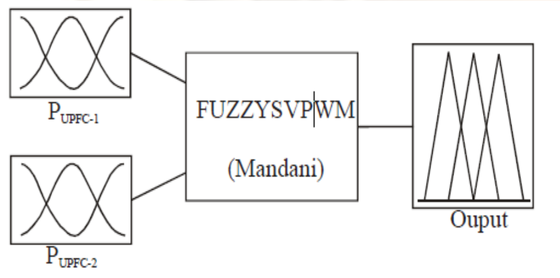

Fig. A: Membership functions of inputs and output

2) Choose membership functions to represent the inputs in fuzzy set notation. Triangular functions are chosen in this work. Fuzzy representations of generator speed change, acceleration, and output variable have been illustrated in Fig. A. Similar membership functions for the other inputs and the stabilizer output are also defined.

3) A set of decision rules relating the inputs to the output are compiled and stored in the memory in the form of a "decision surface". The decision surface is provided in Fig. B.

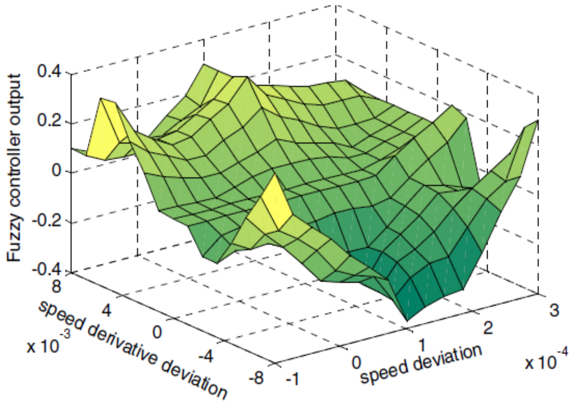

Fig. B .The decision surface is provided in fuzzy controller

IV. UPFC CONTROLLERS

Fig. 4 shows the schematic diagram of the UPFC control system. It comprises of three controllers,
1. Power flow controller
2. DC voltage regulator
3. Power system oscillation damping controller.

A. Power Flow Controller

The power flow controller regulates the power flow on the line in which UPFC is installed. The real power flow is controlled by varying phase angle δB of the series injectedvoltage, keeping the magnitude of the injected voltage constant. Proportional-Integral (P-I) type power flow controller has been considered (Fig. 5). kpp and kpi are the proportional and integral gain settings of the power flow controller. u is the stabilizing signal from damping controller.

B. DC Voltage Regulator

In order to maintain the real power balance between two converters, a DC voltage regulator is incorporated. The DC voltage regulation is achieved by modulating the phase angle of shunt converter voltage. Fig. 6 shows the transfer function of P-I type DC voltage regulator. kdp and kdi are the proportional and integral gain settings of the DC voltage regulator.
C. Power System Oscillation Damping Controller

Power system oscillations can be damped, by producing a torque in phase with the speed deviation. Choice of easily measurable input signal is the main consideration in the design of any damping controller. In the present work, power flow on the line, which can be locally measured, has been used as an input signal to UPFC based damping controller. Fig. 7 shows the transfer function block diagram of UPFC based damping controller.

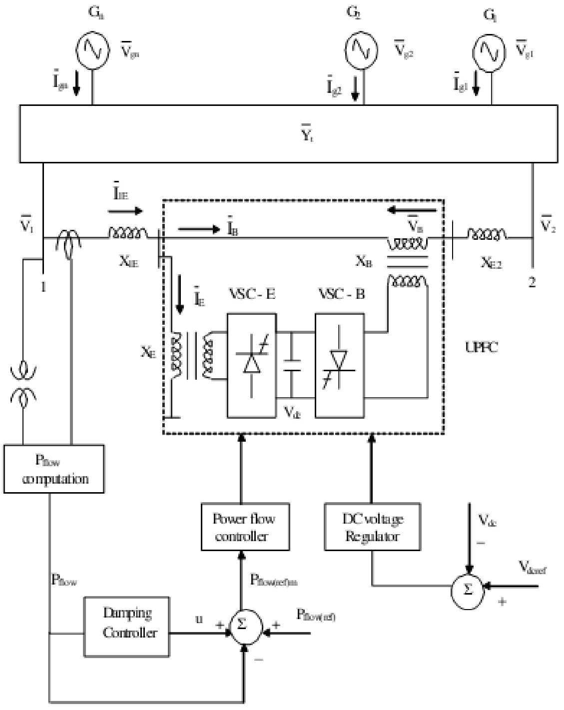

Fig 4: Schematic diagram of an UPFC control system

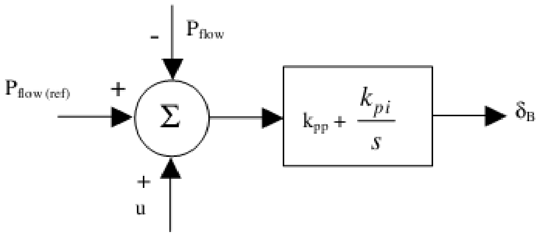

Fig 5: Structure of power flow controller

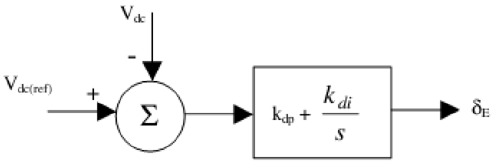

Fig 6: Structure of DC voltage regulator

It comprises of a gain block, signal washout and phase compensator. The parameters of phase compensator are chosen so as to compensate the phase shift provided by the forward path of the closed loop system. The gain setting of the damping controller is chosen such that, the desired damping of the electromechanical mode of concern is obtained, without affecting the damping of the other modes. The output of the damping controller modulates the reference setting of the power flow controller .

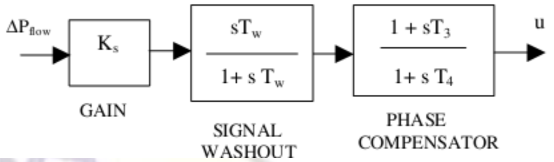

Fig 7: Transfer function block diagram of the UPFC based Damping controller

V. ANALYSIS

A. Optimum Location and Settings of PSS

Before carrying out investigation with UPFC controllers, the optimum location and parameters of PSS have been obtained in this section. The optimum locations of PSS in the system studied are obtained using a residue technique [17]. A residue is defined as the product of magnitudes of controllability and observability indices for the oscillation mode of concern. For each installing location residue is computed for the poorly damped modes of oscillations. The optimum location is the one for which the residue is maximum. The machines 2 and 3 are the optimum locations for the installation of PSS. The transfer function of the PSS is given below:

$$\frac{Vs}{\Delta\omega} = K_{stab}\left(\frac{10s}{1+10s}\right)\left(\frac{1+sT_1}{1+sT_2}\right)^2$$

The optimum parameters of PSS have been obtained (Table 1) using multi-modal decomposition and phase compensation techniques [13,14].

Table 1: Optimum parameters of PSS

PSS	Kstab	T_1(Seconds)	T_2(Seconds)
PSS at machine 2	3	0.2790	0.1115
PSS at machine 3	4	0.1701	0.0523

UPFC controllers are now designed considering PSS locations at generators 2 and 3 with their optimum settings as given in Table 1.

B. Determination of Steady State Operating Condition

For obtaining the desired power flow on a given line under steady state conditions, it is necessary to compute the magnitude of series and shunt injected voltages and their phase angles. In the present work, a generalized load flow program based on Newton-Raphson technique with embedded UPFC [15] has been developed. It may be noted that power flow on line 7-8 without UPFC is 0.7638 p.u. Considering the desired power flow on line 7-8, i.e. P78 = 0.84 p.u. (10% more than the power flow without UPFC), the series and shunt source voltages are obtained as VB = 0.1108 ∟-97.8° and VE = 0.974∟3°. For this initial operating condition, the constants of the system model have been computed.

C. Optimization of UPFC Controllers

The UPFC power flow controller and DC voltage regulator are designed using Gradient type Newton Algorithm [18,19].

(1) Optimization of Power Flow Controller Parameters

In order to obtain optimum proportional and integral gain settings of the power flow controller, the following cost function is considered.

$$J = \int_0^{\infty} (\Delta P_{flow\,(ref)} - \Delta P_{flow})^2\, dt \cdots (7)$$

For any Newton type iterative method, the initial guess of the parameters to be optimized should be closer to the optimum values. In the present study, the initial values of proportional and integral gain settings kpp and kpi are obtained by trial and error approach by dynamic simulation of the system with PSS and power flow controller considering a 5% step increase in reference setting of power flow in line 7-8 (i.e. ΔPflow(ref) = 0.05 p.u.) The proportional and integral gain settings obtained by trial and error approach i.e. kpp0 = 1.0 and kpi0 = -10 are considered as the initial guess. Optimum values of the proportional and integral gain settings of the power flow controller obtained are kpp * = 2.5 and kpi * = -15.

(2) Optimization of DC Voltage Regulator Parameters

To optimize the proportional and integral gains kdp and kdi of the P-I type DC voltage regulator, the cost function is given as:

$$J = \int_0^{\infty} (\Delta V_{dc})^2 dt \quad \cdots (8)$$

ΔVdc is obtained by solving the state space equation with PSS, power flow controller and DC voltage regulator for a 5% step perturbation in Pflow(ref). The initial guess for DC voltage regulator parameters (kdp0 = -0.5 and kdi0 = -15) is made following the same approach given in section C(1). While optimizing DC voltage regulator parameters, power flow controller parameters are set at their optimum values. The optimum proportional and integral gain settings of DC voltage regulator are obtained as kdp * = -1 and kdi * = -10.

E. Dynamic Performance of the System with Power Flow Controller and DC Voltage Regulator

The dynamic responses for ΔPflow in line 7-8 (Fig. 8) are obtained with (a) power flow controller alone and (b) power flow controller and DC voltage regulator operating simultaneously considering a 5% step increase in power flow controller reference setting (i.e. ΔPflow(ref) = 0.05 p.u.) It can be clearly seen from Fig. 8 that the power flow on line 7-8 is regulated to the desired value i.e. under steady state condition the power flow on line 7-8 is increased by 5%. However, the response for ΔPflow with power flow controller alone is somewhat better as compared to the one obtained with power flow controller and DC voltage regulator operating simultaneously. Fig. 9 shows the dynamic responses for deviation in dc link voltage ΔVdc considering the operation of the system with (a) power flow controller alone and (b) power flow controller and DC voltage regulator operating simultaneously. The responses clearly show that the deviation in dc link voltage is regulated to zero when DC voltage regulator is operating along with the power flow controller. At this stage it is considered necessary to reiterate that the DC voltage must be regulated to maintain the real power balance between shunt and series converters. In order to examine the effect of DC voltage regulator on the dynamic performance of the system, the dynamic responses for Δω12 (Fig. 10) are obtained considering a 5% step increase in Pflow(ref) with (a) power flow controller alone and (b) power flow controller and DC voltage regulator operating simultaneously.

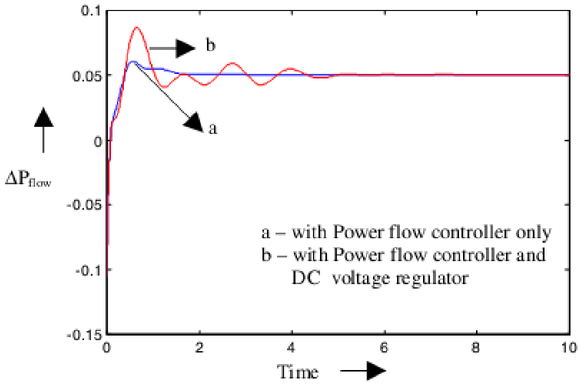

Fig 8: Dynamic responses for Δ Pflow considering a 5% step increase in Pflow(ref)

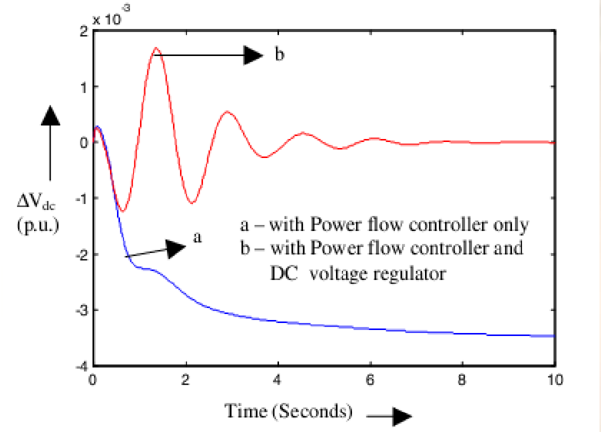

Fig. 9 Dynamic resposes for Δ Vdc following a 5% step increase in Pflow(ref) (Δ Pflow(ref) = 0.05 p.u.)

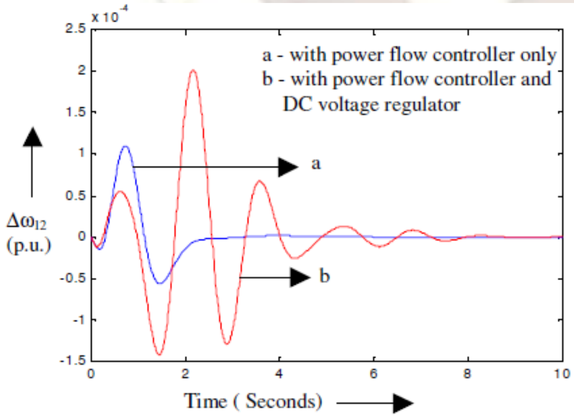

Fig. 10 Dynamic responses for Δω12 considering a 5% step increase in Pflow(ref) (ΔPflow(ref) = 0.05 p.u.)

The above studies clearly show that the damping of the dynamic responses for Δω12 (Fig10) is adversely affected by the incorporation of DC voltage regulator. This may be attributed to adverse interaction between the DC voltage regulator and PSS. The system damping can be improved either by retuning the PSS or by incorporating UPFC based damping controller. The optimization of UPFC based damping controller using multi-modal decomposition and phase compensation techniques is explained in the next section.

F. Design of UPFC based Damping Controller

Table 2 shows the eigenvalues corresponding to oscillatory modes of the system with PSS, power flow controller and DC voltage regulator. It can be clearly seen from Table 2 that all the modes are well damped except the modes -0.698 • } j 3.98 and -0.700 • } j 5.55, which are somewhat weakly damped. The UPFC based damping controller is now designed to improve the damping of the mode -0.700 • } j5.55 i.e. the weakest mode. While optimizing the parameters of UPFC based damping controller, the PSS, power flow controller and DC voltage regulator are set at their optimum values. The controllable parameters of UPFC (i.e. mB, mE, δB and δE) can be modulated in order to produce the damping torque. However, UPFC bus, i.e. bus 7 (Fig. 1) is assumed to be the voltage controlled bus and hence the magnitude of this bus voltage is not modulated. Therefore the remaining three of the four parameters are considered for designing damping controllers. The concept of controllability index [20] is used to select the most suitable control parameter which when modulated, provides the most effective damping characteristics. Table 3 shows the controllability index for three alternative control parameters corresponding to the oscillatory mode of concern.

Table 3 clearly shows that the controllability index for control parameter ΔδB is insignificant as compared to the control parameters ΔmB and ΔδE. Hence the effect of modulation of the control parameter ΔδB is quite insignificant in damping the oscillations. The controllability index is highest for control parameters ΔmB. Hence ΔmB is chosen as output signal of the damping controller. Deviation in power flow on line 7-8 is

Table 2: Eigenvalues of the system with PSS, Power flow controller and DC voltage regulator, pertaining to oscillatory modes.

Eigen values	Damping ratio of oscillatory modes	Natural frequency of oscillations (rad/sec)
-0.698 + j 3.98	0.173	4.04
-0.700 + j 5.55	**0.125**	**5.60**
-1.70 + j 0.721	0.920	1.84
-2.01 + j 2.53	0.622	3.23
-6.00 + j 6.50	0.678	8.84
-12.54 + j 3.93	0.953	13.1
-15.6 + j 14.1	0.743	21.0

Table3: Controllability indices and different controllable parameters.

Control parameters of UPFC	Controllability index
Δm_B	**0.1640**
$\Delta \delta_E$	0.1548
$\Delta \delta_B$	0.0022

considered as the input signal to the damping controller. The multi-modal decomposition and phase compensation techniques [13-14] have been used to optimize the parameters of UPFC based damping controller. The optimum gain and time constants of the UPFC based damping controller obtained are, Ks * = 0.1, T3 * = 0.1885 sec and T4 * = 0.2245 sec.

G. Dynamic Performance of the System with Damping Controller

The dynamic performance of the system is now examined considering

(a) PSS, power flow controller and DC voltage regulator

(b) PSS, power flow controller, DC voltage regulator and UPFC based damping controller

for ΔPflow(ref) = 0.05 p.u. (Fig. 11). It is evident from Fig. 11 that with the incorporation of UPFC based damping controller the desired damping performance is obtained

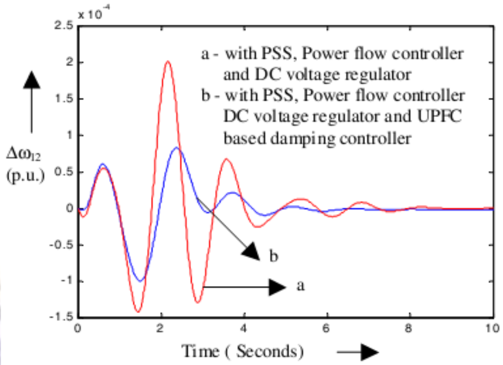

Fig. 11 Dynamic responses for Δ ω12 with and without UPFC based damping controller for Δ Pflow(ref) = 0.05 p.u.

J. Dynamic Performance of the System with Fuzzy Controller.

(a) PSS, power flow controller, DC voltage regulator and UPFC based damping fuzzy controller

For ΔP flow(ref) = 0.05 p.u. (Fig. 11). It is evident from Fig. 12 that with the incorporation of UPFC based damping fuzzy controller the desired damping performance is obtained.

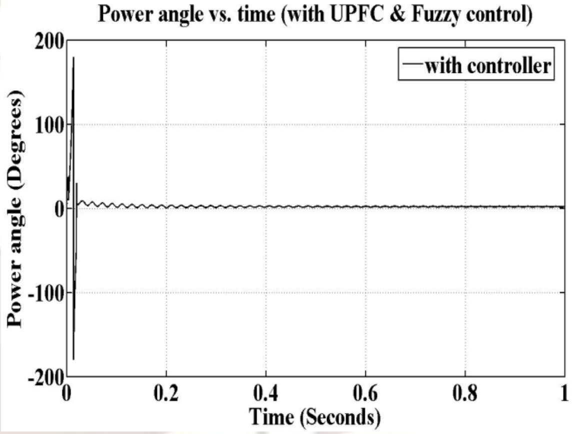

Fig.12. power angle damping with fuzzy controller.

VI CONCLUSIONS

The significant contributions of the research work presented in this paper are as follows:

1. A comprehensive approach for optimum design of UPFC controllers (i.e. power flow controller, DC voltage regulator and damping controller) has been presented for a multimachine system.

2. The interaction between the PSS and UPFC with fuzzy controllers has been studied. The studies reveal that DC voltage regulator interacts negatively with PSS thereby deteriorating the overall damping of the system. The adverse interaction between PSS and DC voltage regulator has been compensated, by providing UPFC based damping controller.

3. The relative effectiveness of UPFC control parameters (ΔmB, ΔδB and ΔδE) for damping the low frequency oscillations has been examined, considering a controllability index. Investigations reveal that control parameter ΔmB is most effective in damping oscillations with fuzzy logic technique.

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