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UPFC Control based on New IP Type Controller

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Abstract – This paper presents the application of Unified Power Flow Controller (UPFC) in order to simultaneous control of power flow and voltage and also damping of Low Frequency Oscillations (LFO) at a Single-Machine Infinite-Bus (SMIB) power system installed with UPFC. PI type controllers are commonly used controllers for UPFC control. But for the sake of some drawbacks of PI type controllers, the scope for finding a better control scheme still remains. In this regard, in this paper the new IP type controllers are considered as UPFC controllers. The parameters of these IP type controllers are tuned using Genetic Algorithms (GA). Also a stabilizer supplementary controller based UPFC is considered for increasing power system damping. To show the ability of IP controllers, this controller is compared with classical PI type controllers. Simulation results emphasis on the better performance of IP controller in comparison with PI controller.

Keywords: IP controller, Low frequency oscillations, Power flow control, Unified power flow controller, Voltage control

1. Introduction

The rapid development of the high-power electronics industry has made Flexible AC Transmission System (FACTS) devices viable and attractive for utility applications. FACTS devices have been shown to be effective in controlling power flow and damping power system oscillations. In recent years, new types of FACTS devices have been investigated that may be used to increase power system operation flexibility and controllability, to enhance system stability and to achieve better utilization of existing power systems [1]. 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. But 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 [2-6]. Low Frequency Oscillations (LFO) 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 [7-10]. They are designed for a specific operating condition using linear models. More advanced control schemes such as Particle-Swarm method, Fuzzy logic and genetic algorithms [11-14] offer better dynamic performances than fixed parameter controllers.

The objective of this paper is to investigate the ability of UPFC for power flow control, voltage support and damping of power system oscillations at the same time. In this paper the UPFC internal controllers (power flow controller, bus-voltage controller and DC link voltage regulator) are considered as IP type controllers. GA is handled for tuning the parameters of these IP type controllers. Also a supplementary stabilizer controller based on UPFC is considered for damping of power system oscillations and stability enhancement. Different load conditions are considered to show ability of UPFC and also comparing IP and PI controllers. Simulation results show the effectiveness of UPFC in power system stability and control.

2. System under study

Fig. 1 shows a SMIB power system installed with UPFC [1]. The UPFC is installed in one of the two parallel transmission lines. This configuration (comprising two parallel transmission lines) permits to control of real and reactive power flow through a line. The nominal system parameters are given in appendix.

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3. Dynamic model of the system

3.1 Nonlinear dynamic model

A non-linear dynamic model of the system is derived by disregarding the resistances of all components of the system (generator, transformers, transmission lines and converters) and the transients of the transmission lines and transformers of the UPFC [15, 16]. The nonlinear dynamic model of the system installed with UPFC is given as (1).

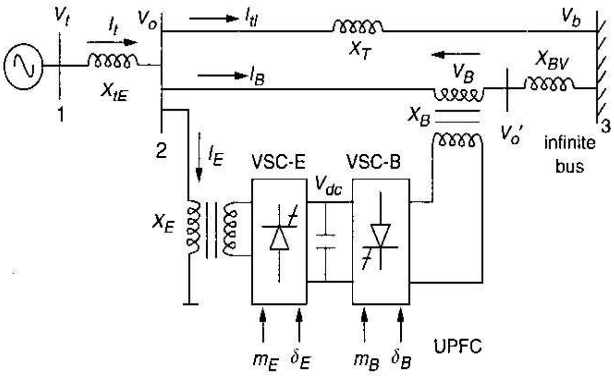

Fig. 1. A Single Machine Infinite Bus (SMIB) power system installed with UPFC in one of the lines

$$\begin{cases} \dot{\omega} = \dfrac{\left(P_m - P_e - D\Delta\omega\right)}{M} \\ \dot{\delta} = \omega_0\left(\omega - 1\right) \\ \dot{E}_q' = \dfrac{\left(-E_q + E_{fd}\right)}{T_{do}'} \\ \dot{E}_{fd} = \dfrac{-E_{fd} + K_a\left(V_{ref} - V_t\right)}{T_a} \\ \dot{V}_{dc} = \dfrac{3m_E}{4C_{dc}}\left(\sin\left(\delta_E\right)I_{Ed} + \cos\left(\delta_E\right)I_{Eq}\right) + \dfrac{3m_B}{4C_{dc}} * \\ \left(\sin\left(\delta_B\right)I_{Bd} + \cos\left(\delta_B\right)I_{Bq}\right) \end{cases} \tag{1}$$

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

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

3.2 Linear dynamic model

A linear dynamic model is obtained by linearizing the nonlinear dynamic model around the nominal operating condition. The linear model of the system is given as (3).

$$\begin{cases} \Delta\dot{\delta} = w_0\Delta w \\ \Delta\dot{\omega} = \left(-\Delta P_e - D\Delta\omega\right)/M \\ \Delta\dot{E}_q^{/} = (-\Delta E_q + \Delta E_{fd})/T_{do}^{/} \\ \Delta\dot{E}_{fd} = -\dfrac{1}{T_A}\Delta E_{fd} - \dfrac{K_A}{T_A}\Delta V \\ \Delta\dot{v}_{dc} = K_7\Delta\delta + K_8\Delta E_q^{/} - K_9\Delta v_{dc} + K_{ce}\Delta m_E + \\ K_{c\delta e}\Delta\delta_E + K_{cb}\Delta m_B + K_{c\delta b}\Delta\delta_B \end{cases} \tag{3}$$

Fig. 2 shows the transfer function model of the system including UPFC. The model has numerous constant parameters denoted by K_{ij}. These constant parameters are function of the system parameters and the initial operating condition. Also the control vector U in Fig. 2 is defined as (4).

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

Where:

ΔmB: Deviation in pulse width modulation index mB of series inverter. By controlling mB, the magnitude of series-injected voltage can be controlled.

$\Delta\delta$B : Deviation in phase angle of series injected voltage.

ΔmE : Deviation in pulse width modulation index mE of shunt inverter. By controlling mE, 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.

The dynamic model of the system in state-space form is as (5). It should be noted that in this paper, the linear model is used to study and the results are obtained by using linear model. Also, application of nonlinear model is better for large signal stability analysis. But in this paper, small signal stability analysis is evaluated.

$$\begin{bmatrix} \Delta\dot{\delta} \\ \Delta\dot{\omega} \\ \Delta\dot{E}_q^{/} \\ \Delta\dot{E}_{fd} \\ \Delta\dot{V}_{dc} \end{bmatrix} = \begin{bmatrix} 0 & w_0 & 0 & 0 & 0 \\ -\frac{K_1}{M} & 0 & -\frac{K_2}{M} & 0 & -\frac{K_{pd}}{M} \\ -\frac{K_4}{T_{do}^{/}} & 0 & -\frac{K_3}{T_{do}^{/}} & \frac{1}{T_{do}^{/}} & -\frac{K_{qd}}{T_{do}^{/}} \\ -\frac{K_A K_5}{T_A} & 0 & -\frac{K_A K_6}{T_A} & -\frac{1}{T_A} & -\frac{K_A K_{vd}}{T_A} \\ K_7 & 0 & K_8 & 0 & -K_9 \end{bmatrix} \times \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta E_q^{/} \\ \Delta E_{fd} \\ \Delta v_{dc} \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 & 0 \\ -\frac{K_{pe}}{M} & -\frac{K_{p\delta e}}{M} & -\frac{K_{pb}}{M} & -\frac{K_{p\delta b}}{M} \\ -\frac{K_{qe}}{T_{do}^{/}} & -\frac{K_{q\delta e}}{T_{do}^{/}} & -\frac{K_{qb}}{T_{do}^{/}} & -\frac{K_{q\delta b}}{T_{do}^{/}} \\ -\frac{K_A K_{ve}}{T_A} & -\frac{K_A K_{v\delta e}}{T_A} & -\frac{K_A K_{vb}}{T_A} & -\frac{K_A K_{v\delta b}}{T_A} \\ Kce & K_{c\delta e} & K_{cb} & K_{c\delta b} \end{bmatrix} \times \begin{bmatrix} \Delta m_E \\ \Delta\delta_E \\ \Delta m_B \\ \Delta\delta_B \end{bmatrix} \tag{5}$$

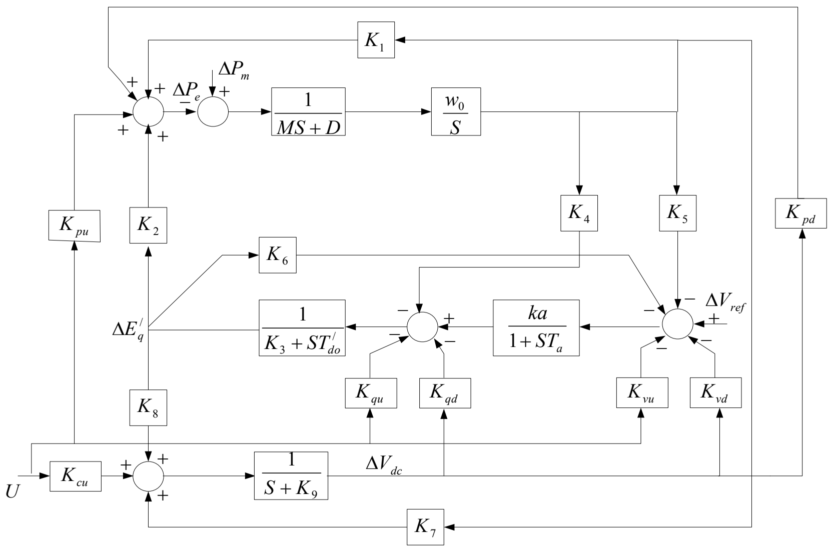

Fig. 2. Transfer function model of the system including UPFC

4. IP Controller

As referred before, in this paper IP type controllers are considered as UPFC internal controllers. Fig. 3 shows the structure of IP controller. It has some clear differences with PI controller. In the case of IP regulator, at the step input, the output of the regulator varies slowly and its magnitude is smaller than the magnitude of PI regulator at the same step input [17]. Also as shown in Fig. 4, If the outputs of the both regulators are limited as the same value by physical constraints, then compared to the bandwidth of PI regulator the bandwidth of IP regulator can be extended without the saturation of the regulator output [17].

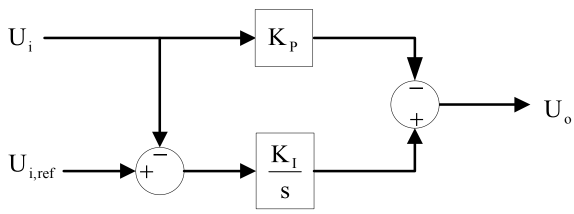

Fig. 3. Structure of the IP controller

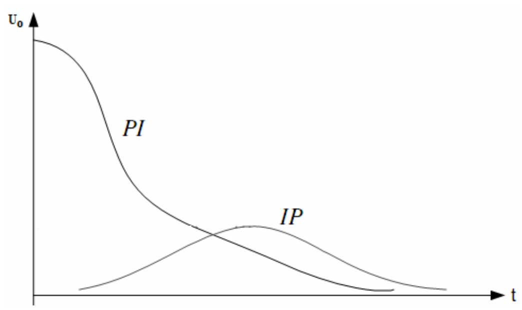

Fig. 4. Output of IP and PI regulators with the same damping coefficient ($\xi = 1$) and the same band width at the same step input signal command [17]

5. UPFC Controller

In this research four control strategies are considered for UPFC:

- Power Flow Controller
- Bus voltage controller
- DC voltage regulator
- Power system oscillation-damping controller

5.1 Internal UPFC controllers

UPFC has three internal controllers which are Power Flow Controller, Bus voltage controller and DC voltage regulator. In this paper IP type controllers are considered for UPFC control problem. Fig. 5 shows the structure of the power flow controller. The power flow controller regulates the power flow on the line which UPFC is installed. 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. Fig. 6 shows the structure of the DC-voltage regulator. Fig. 7 shows the structure of the generator terminals voltage controller. The generator terminals voltage controller regulates the voltage of generator terminals during post fault in system.

5.2 Power system oscillations-damping controller

A stabilizer controller is provided to improve damping of power system oscillations and stability enhancement. This controller is considered as a lead-lag compensator. This stabilizer provides an electrical torque in phase with the speed deviation in order to improve damping of power system oscillations. The transfer function model of the stabilizer controller is shown in Fig. 8.

6. Analysis

For the nominal operating condition the eigen-values of the system are obtained using state-space model of the system presented in (5) and these eigen-values are listed in Table 1. It is seen that the system is unstable and needs to power system stabilizer (damping controller) for stability.

Table 1. Eigen-values of the closed-loop system

-15.3583, -5.9138, -0.7669
+0.7542 ± 3.3055i

6.1 Design of damping controller for stability

The damping controllers are designed to produce an electrical torque in phase with the speed deviation according to phase compensation method. 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 damping controller design also the speed deviation $\Delta\omega$ is considered as the input to the damping controllers. The structure of damping controller has been shown in Fig. 8. It consists of gain, signal washout and phase compensator block. The parameters of the 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 [18]. Damping controller has been designed and obtained as (6).

$$\text{damping controller} = \frac{481.3021 \quad s \quad (s+4.712)}{(s+0.1) \quad (s+5.225)} \tag{6}$$

The eigen-values of the system with stabilizer controller are listed in Table 2 and it is clearly seen that the system is stable.

Table 2. Eigen-values of the closed-loop system with stabilizer controller

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

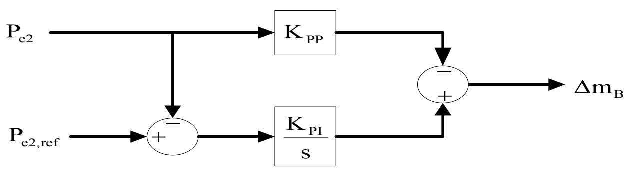

Fig. 5. Power flow controller

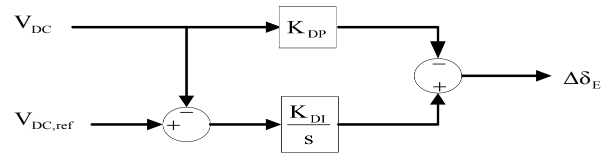

Fig. 6. DC-voltage regulator

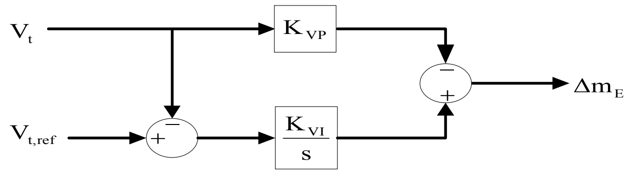

Fig. 7. Generator terminals voltage controller

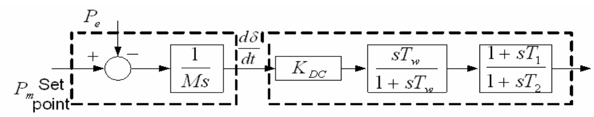

Fig. 8. Stabilizer controller

7. Internal UPFC Controllers Design

After system stabilizing, the next step is to design the internal UPFC controllers (power flow controller, DC voltage regulator and generator terminals voltage controller). As mentioned before, IP type controllers are considered for UPFC and these controllers are tuned using GA. In the next section an introduction about GA is presented.

7.1 Genetic algorithms

Genetic Algorithms (GA) are global search techniques, based on the operations observed in natural selection and genetics [19]. They operate on a population of current approximations-the individuals-initially drawn at random, from which improvement is sought. Individuals are encoded as strings (Chromosomes) constructed over some particular alphabet, e.g., the binary alphabet {0.1}, so that chromosomes values are uniquely mapped onto the decision variable domain. Once the decision variable domain representation of the current population is calculated, individual performance is assumed according to the objective function which characterizes the problem to be solved. It is also possible to use the variable parameters directly to represent the chromosomes in the GA solution. At the reproduction stage, a fitness value is derived from the raw individual performance measure given by the objective function and used to bias the selection process. Highly fit individuals will have increasing opportunities to pass on genetically important material to successive generations. In this way, the genetic algorithms search from many points in the search space at once and yet continually narrow the focus of the search to the areas of the observed best performance. The selected individuals are then modified through the application of genetic operators. In order to obtain the next generation Genetic operators manipulate the characters (genes) that constitute the chromosomes directly, following the assumption that certain genes code, on average, for fitter individuals than other genes. Genetic operators can be divided into three main categories: Reproduction, crossover and mutation [19].

7.2 Controllers adjustment using GA

In this section the parameters of the proposed IP type controllers are tuned using GA. All three IP controllers are simultaneously tuned using GA. the procedure of parameters tuning using GA is as follow steps:

- Generating an initial population as random
- Calculation of performance index for each chromosome in the population
- Finding the minimum objective function and related chromosome
- Performing mating and mutation
- Updating the population
- Repeating the process till convergence

In GA method, each row of the population is called a chromosome. Number of chromosomes is chosen by designer. Also, number of columns depends to the number of parameters.

After creating the population, the cost of each chromosome is calculated by using objective function. Then the chromosomes with lower cost are chosen as better individuals to generate new children.

Crossover rate indicates the number of chromosomes which are remains to generate new children. Generating new child is perfumed based on the following rule:

New chromosome = (father chromosome) λ+ (mother chromosome) (1-λ)

Father and mother chromosomes are chosen from elites and λ is a random number between 0 and 1.

Mutation rate indicates number of randomly generated chromosomes to avoid converging to the local minima.

In this study the performance index is considered as (7). In fact, the performance index is the Integral of the Time multiplied Absolute value of the Error (*ITAE*).

$$\mathrm{ITAE} = \int_0^t t|\Delta\omega|\,dt + \int_0^t t|\Delta V_{DC}|\,dt + \int_0^t t|\Delta P_e|\,dt + \int_0^t t|\Delta V_t|\,dt \tag{7}$$

Where, Δω is the frequency deviation, ΔVDC is the deviation of DC voltage, ΔVt is the deviation of bus voltage, ΔPe2 is the deviation of electrical power in line 2 and parameter "t" in ITAE is the simulation time. It is clear to understand that the controller with lower ITAE is better than the other controllers. To compute the optimum parameter values, a 0.1 step change in mechanical torque (ΔTm) is assumed and the performance index is minimized using GA. In order to acquire better performance, number of iterations, population size, crossover rate and mutation rate are chosen as 100, 50, 0.6 and 0.15 respectively. The optimum values resulting from minimizing the performance index are presented in Table 3. In order to show effectiveness of IP method, the classical PI type controllers are also considered for UPFC control and the parameters of these PI type controllers are tuned using GA. The results are listed in Table 4.

Table 3. Optimum values of IP type controllers

IP controller of power flow	K_{PP}	0.0788
	K_{PI}	4.1718
IP controller of DC voltage	K_{DP}	9.8655
	K_{DI}	25.15
IP controller of Bus voltage	K_{VP}	1.5966
	K_{VI}	29.2421

Table 4. Optimum values of PI type controller

PI controller of power flow	K_{PP}	0.2070
	K_{PI}	4.7776
PI controller of DC voltage	K_{DP}	2.0757
	K_{DI}	0.9419
PI controller of Bus voltage	K_{VP}	0.2524
	K_{VI}	31.1230

8. Results and Discussions

In order to evaluate the effectiveness of UPFC and also comparing IP and PI controllers, numerous scenarios are considered for simulation and also in order to study and analysis system performance under system uncertainties (controller robustness); two operating conditions are considered as follows:

- Scenario 1: Nominal operating condition
- Scenario 2: Heavy operating condition

The parameters for these two scenarios are presented in appendix. It should be note that IP and PI controllers have been designed for the nominal operating condition. In order to demonstrate the robustness performance of the proposed methods, The *ITAE* is calculated following 5% step change in the reference power of line 2 (ΔP_{e2}) at all operating conditions (Nominal and Heavy) and results are shown at Table 5. Following step change, the IP controller has better performance than PI at all operating conditions.

Table 5. The calculated ITAE index for the both controllers

	IP	PI
Nominal operating condition	0.000242	0.0034
Heavy operating condition	0.000244	0.0042

The other important factor in the comparison of controllers is control effort signal. In this paper following index is considered to compare of the IP and PI controllers.

$$\text{Control Effort} = \int_0^t t\left|\Delta u\right| dt \qquad (8)$$

Where, *u* shows the control signal. The proposed index is calculated for the both PI and IP controllers. The results are listed in Table 6. The results show that the IP controller injects a lower control signal. Thus, in the case of IP controller, it is less probable to saturation of control signal.

Also simulation results following 0.05 step change in the reference power of line 2 (Pe2ref) in the nominal operating condition are shown in Figs. 9-12. Fig. 9 shows the power of line 2 changes from zero to 0.05 after 0.05 step change in the reference power of line 2, therefore UPFC can successfully alters the power flow of line 2 based the command reference. Fig. 10 shows that the DC voltage of UPFC goes back to zero after disturbances and the steady state error has been removed and Fig. 11 shows the voltage of generator bus which is driven back to zero after oscillations. The results show that UPFC can simultaneously control power flow, bus voltage and DC voltage. Fig. 12 shows the deviation of synchronies speed and it is seen that the supplementary stabilizer greatly enhances the damping of the oscillations and therefore the system becomes more stable and robust. In all cases the IP method has better performance than PI method in control of power system and also stability enhancement.

Table 6. The calculated control effort signal for the both controllers

	IP	PI
Nominal operating condition	2.0577	2.0711
Heavy operating condition	2.1602	2.1741

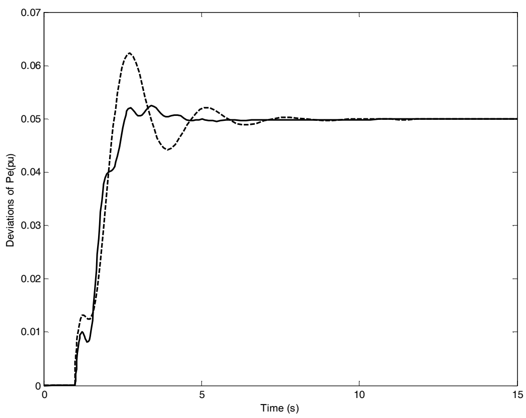

Fig. 9. Dynamic response ΔP_{e2} following 5% step change in the reference power of line 2 Solid line (IP controller), dashed line (PI controller)

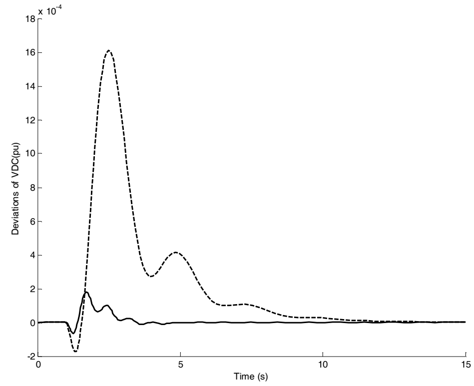

Fig. 10. Dynamic response ΔV_{DC} following 5% step change in the reference power of line 2 Solid line (IP controller), dashed line (PI controller)

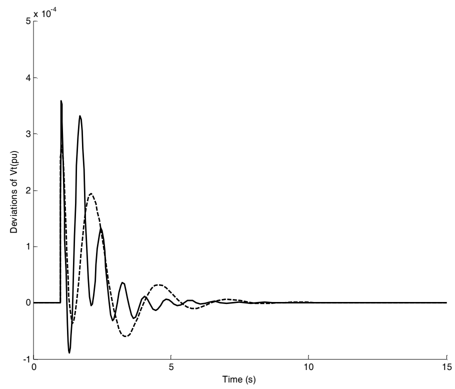

Fig. 11. Dynamic response ΔV_t following 5% step change in the reference power of line 2 Solid line (IP controller), dashed line (PI controller)

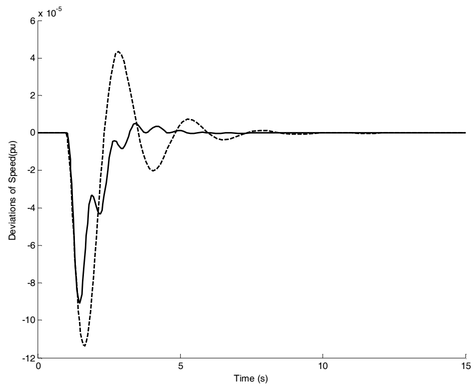

Fig. 12. Dynamic response $\Delta\omega$ following 5% step change in the reference power of line 2 Solid line (IP controller), dashed line (PI controller)

9. Conclusions

In this paper UPFC successfully incorporated in order to simultaneous control of power flow, bus voltage and DC voltage. Also a supplementary stabilizer based UPFC incorporated for damping power system oscillations.

Internal UPFC controllers modeled as IP type and their parameters tuned using GA. The simulation results showed that the UPFC with IP controllers has better performance in control and stability than UPFC with PI controllers. The multi objective abilities of UPFC in control and stability successfully were showed by time domain simulation.

Acknowledgements

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Appendix

The nominal system parameters are listed in Table 7. Also the system operating conditions are defined as Table 8 (Operating condition 1 is the nominal operating condition).

Table 7. System parameters

Generator	$M = 8$ Mj/MVA	$T'_{do} = 5.044$ s	$X_d = 1$ p.u.
	$X_q = 0.6$ p.u.	$X'd = 0.3$ p.u.	$D = 0$
Excitation system		$K_a = 10$	$T_a = 0.05$ s
Transformers		$X_{te} = 0.1$ p.u.	$X_{SDT} = 0.1$ p.u.
Transmission lines		$X_{T1} = 1$ p.u.	$X_{T2} = 1.25$ p.u.
DC link parameters		$V_{DC} = 2$ p.u.	$C_{DC} = 3$ p.u.
UPFC parameters		$m_E = 1.0224$ $\delta_E = 22.24^\circ$	$m_B = 0.142$ $\delta_B = -48.61^\circ$

Table 8. System operating conditions

Operating condition	$P = 1$ p.u.	$Q = 0.2$ p.u.	$V_t = 1.03$ p.u.
Operating condition	$P = 1.08$ p.u.	$Q = 0.25$ p.u.	$V_t = 1.03$ p.u.

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