International Journal of the Physical Sciences Vol. 6(10), pp. 2363-2371, 18 May, 2011
Available online at http://www.academicjournals.org/IJPS
DOI: 10.5897/IJPS11.467
ISSN 1992 - 1950 ©2011 Academic Journals

Full Length Research Paper

Multi objective control of UPFC using PID type controllers

Meysam Eghtedari, Reza Hemmati* and Sayed Mojtaba Shirvani Boroujeni

Department of Electrical Engineering, Boroujen Branch, Islamic Azad University, Boroujen, Iran.

Accepted 22 April, 2011

This paper presents the application of Unified Power Flow Controller (UPFC) in order to simultaneously power flow control, voltage support and also transient stability improvement at a Single-Machine Infinite-Bus (SMIB) power system installed with UPFC. In practical systems, the conventional PI type controllers are considered to control UPFC. In order to overcome the drawbacks of the conventional PI controllers, numerous techniques have been proposed in literatures. In this paper, PID type controller is considered for UPFC control and the parameters of the proposed PID controller are obtained using Particle Swarm Optimization (PSO). To show effectiveness of PID controller, a PI type controller optimized by PSO is designed in order to compare it with the proposed PID controller. The simulation results visibly show the validity of PID controller in comparison with PI controller.

Key words: Flexible AC transmission systems, Unified Power Flow Controller, power flow control, voltage control, transient stability enhancement, low frequency oscillations damping.

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 (Hingorani and GyuGui, 2000). 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, that is, 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 (Alasooly and Redha, 2010; Mehraeen et al., 2010; Jiang et al., 2010; Jiang et al., 2010; Faried and Billinton, 2009). Also UPFC can be used for transient stability improvement by damping of Low Frequency Oscillations (LFO) in power system. 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 (Zarghami et al., 2010; Guo and Crow, 2009; Tambey and Kothari, 2003; Wang, 1999). 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 (Taher et al., 2008; Al-Awami, 2007; Eldamaty et al., 2005) offer better dynamic performances than fixed parameter controllers.

The objective of this paper is to investigate the ability of UPFC for simultaneous control of power flow, voltage support and also damping of power system oscillations. In this paper the UPFC internal controllers (power flow controller, bus-voltage controller and DC link voltage regulator) are considered as PID type controllers. The PSO is considered for tuning the parameters of these PID

*Corresponding author. E-mail: reza.hematti@gmail.com. Tel: +983824223812, +989183559624. Fax: +98983824223812.

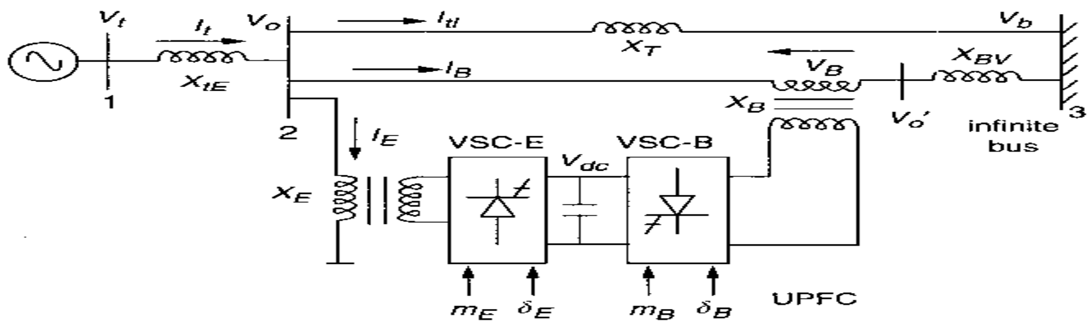

Figure 1. A Single Machine Infinite Bus (SMIB) power system installed with UPFC in one of the lines.

controllers. Also a supplementary stabilizer controller based UPFC is considered for damping of power system oscillations and transient stability improvement. To show effectiveness of the proposed method, PI type controllers optimized by PSO are designed in order to comparison with the proposed PID controllers. Different load conditions are considered to show ability of UPFC and also comparing the performance of PID and PI controllers. Simulation results show the effectiveness of UPFC in power system control and stability enhancement with PID controllers.

SYSTEM UNDER STUDY

Figure 1 shows a SMIB power system installed with UPFC (Hingorani and Gyugui, 2000). The UPFC is installed in one of the two parallel transmission lines. This configuration (comprising two parallel transmission lines) permits control of real and reactive power flow through a line. The nominal system parameters are given in appendix.

DYNAMIC MODEL OF THE SYSTEM

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 (Nabavi-Niaki and Iranvani, 1996; Wang, 2000). The nonlinear dynamic model of the system installed with UPFC is given as Equation (1).

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

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

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

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 Equation (3).

$$\begin{cases} \Delta\dot{\delta} = w_0 \Delta w \\ \Delta\dot{\omega} = (-\Delta P_e - D\Delta\Delta)/M \\ \Delta\dot{E}'_q = (-\Delta E_q + \Delta E_{fd})/T'_{do} \\ \Delta\dot{E}_{fd} = -\dfrac{1}{T_A}\Delta E_{fd} - \dfrac{K_A}{T_A}\Delta V \\ \Delta\dot{v}_{dc} = K_7\Delta\delta + K_8\Delta E'_q - K_9\Delta v_{dc} + K_{ce}\Delta m_E + K_{c\delta\delta}\Delta\delta_E + K_{cb}\Delta m_B + K_{c\delta\delta}\Delta\delta_B \end{cases} \quad (3)$$

Where

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

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

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

Figure 2 shows the transfer function model of the system including UPFC, which is known as Heffron-Phillips model (Heffron and Phillips, 1952). The Heffron-Phillips model of a synchronous machine has successfully been used for investigating the low frequency oscillations and designing power system stabilizers. The parameters of the model are usually calculated using the synchronous generator parameters and some system variables at steady-state conditions. A key feature of the model is its ability to show clearly the effect of excitation control on damping. It has been used to great advantage in numerous studies on the design of supplementary stabilizers for power systems. Also the control vector U in Figure 2 is defined as Equation (4).

$$U = [\Delta m_E \quad \Delta\delta_E \quad \Delta m_B \quad \Delta\delta_B]^T \quad (4)$$

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 pulsewidth modulation index mE of shunt inverter.

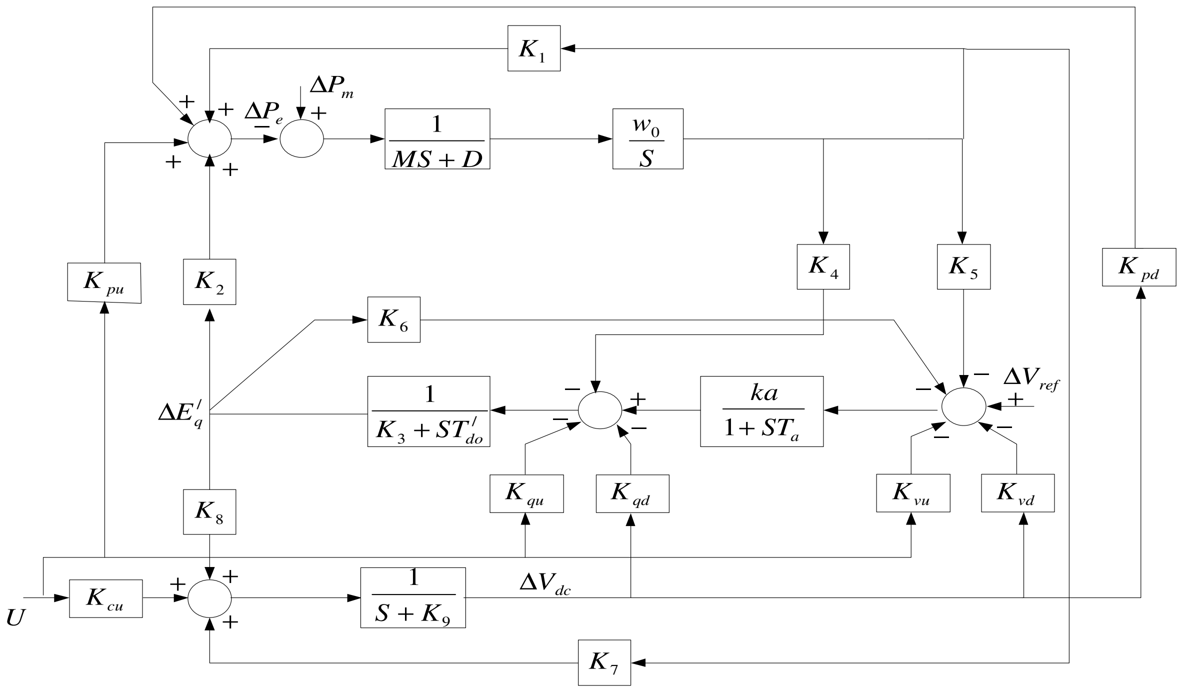

Figure 2. Transfer function model of the system including UPFC.

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.

It should be noted that Kpu , Kqu , Kvu and Kcu in Figure 2 are the row vectors and defined as follow:

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

Dynamic model in state-space form

The dynamic model of the system in state-space form is obtained as Equation (5).

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

PROBLEM STATEMENT

As referred before, in order to suitable utilize UPFC, the UPFC control strategies should be considered and designed. In this research four control strategies are considered for UPFC:

i) Power flow controller
ii) Bus voltage controller
iii) DC voltage regulator
iv) Power system oscillation-damping controller.

UPFC has three internal controllers which are Power flow controller, bus voltage controller and DC voltage regulator. Figure 3 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 should 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 4 shows the structure of the DC-voltage regulator. Figure 5 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.

Also 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 Figure 6.

ANALYSIS

For the nominal operating condition the eigen-values of the system are obtained using state-space model of the system presented in Equation (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.

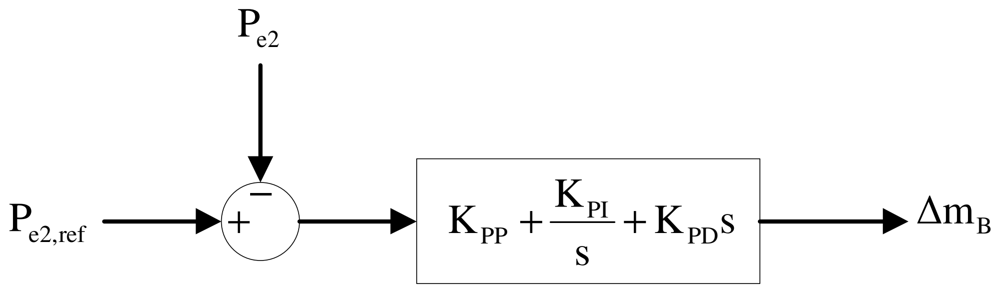

Figure 3. Power flow controller.

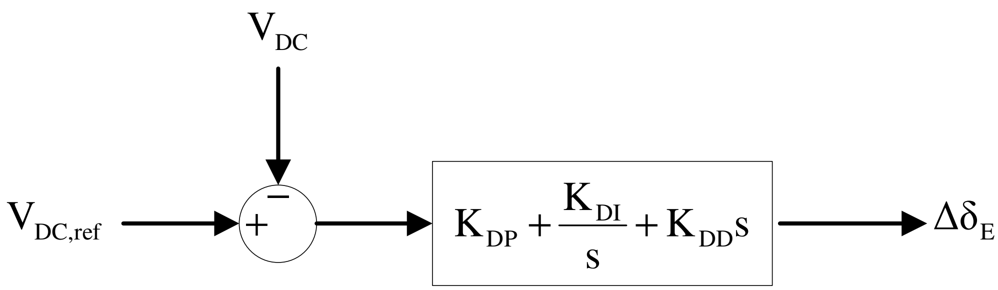

Figure 4. DC-voltage regulator.

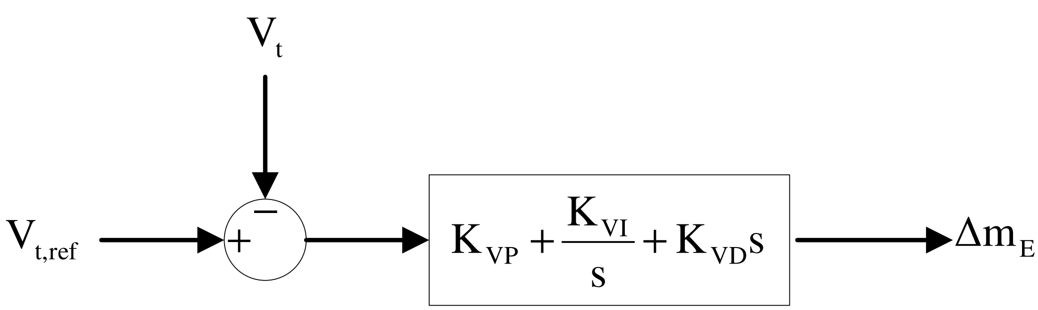

Figure 5. Generator terminals voltage controller.

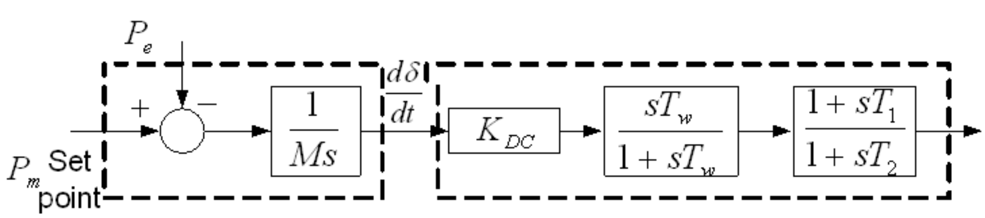

Figure 6. Stabilizer controller.

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 (mB, mE, δB and δE) can be modulated in order to produce the

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

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

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

damping torque. In this study, mB is modulated in order to stabilize controller design; also the speed deviation $\Delta\omega$ is considered as the input to the stabilizer controllers. The structure of stabilizer controller has been shown in Figure 6. 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 (Yu, 1983). Here the damping controller is designed as Equation (6). Also the wash-out parameter (Tw) is considered equal to 10 s.

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

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

Objective of study

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 previously mentioned, PID type controllers are considered for UPFC and these controllers are tuned using PSO.

Particle Swarm Optimization

PSO was formulated by Edward and Kennedy in 1995. The thought process behind the algorithm was inspired by the social behavior of animals, such as bird flocking or fish schooling. PSO is similar to the continuous GA in that it begins with a random population matrix. Unlike the GA, PSO has no evolution operators such as crossover and mutation. The rows in the matrix are called particles (same as the GA chromosome). They contain the variable values and are not binary encoded. Each particle moves about the cost surface with a velocity. The particles update their velocities and positions based on the local and global best solutions as shown in Equations (7) and (8) (Randy and Sue, 2004):

$$V_{m,n}^{new} = w \times V_{m,n}^{old} + \Gamma_1 \times r_1 \times (P_{m,n}^{local\ best} - P_{m,n}^{old}) + \Gamma_2 \times r_2 \times (P_{m,n}^{global\ best} - P_{m,n}^{old}) \qquad (7)$$

$$P_{m,n}^{new} = P_{m,n}^{old} + \Gamma\ V_{m,n}^{new} \qquad (8)$$

Where:
Vm,n = particle velocity
Pm,n = particle variables
W= inertia weight
r1, r2 = independent uniform random numbers
Γ1 = Γ2 = learning factors
Pm,n local best = best local solution
Pm,n global best = best global solution

The PSO algorithm updates the velocity vector for each particle then adds that velocity to the particle position or values. Velocity updates are influenced by both the best global solution associated with the lowest cost ever found by a particle and the best local solution associated with the lowest cost in the present population. If the best local solution has a cost less than the cost of the current global solution, then the best local solution replaces the best global solution. The particle velocity is reminiscent of local minimizations that use derivative information, because velocity is the derivative of position. The advantages of PSO are that it is easy to implement and there are few parameters to adjust. The PSO is able to tackle tough cost functions with many local minima (Randy and Sue, 2004).

Controllers' adjustment using PSO

Here the parameters of the proposed PID type controllers are tuned using PSO. All three PID controllers are simultaneously tuned using PSO. In this paper the performance index is considered as Equation (9). In fact, the performance index is the Integral of the Time multiplied Absolute value of the Error (*ITAE*).

$$ITAE = \int_0^t t|\Delta\omega|dt + \int_0^t t|\Delta V_{DC}|dt + \int_0^t t|\Delta P_e|dt + \int_0^t t|\Delta V_t|dt \qquad (9)$$

Where, $\Delta\omega$ 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 and 100 s time period is considered for simulation. It is clear to understand that the controller with lower ITAE is better than the other controllers. To compute the optimum parameter values, 0.1 step change in the reference power of line 2 (Pe2ref) is assumed and the performance index is minimized using PSO. In order to acquire better performance, number of particle, particle size, number of iteration, Γ1, Γ2, and Γ are chosen as 36, 9, 50, 2, 2 and 1, respectively. Also, the inertia weight, w, is linearly decreasing from 0.9 to 0.4. The optimum values resulting from minimizing the performance index are presented in Table 3. Also in order to show effectiveness of PID controller, a PI type controller is considered for UPFC control and the parameters of these PI controllers are tuned using PSO; and the optimal parameters of PI controllers are obtained as shown in Table 4. Where the boundaries of parameters for optimal search are as follows: 0.1<K<1000. In the PI controllers tuning, the objective function is considered as it for PID controllers tuning.

RESULTS AND DISCUSSION

In order to evaluate the effectiveness of UPFC with PID and PI controllers and also analysis system performance

Table 3. Optimum values of PID controller parameters using PSO.

PID controller of power flow	K_{PP}	4.8436
	K_{PI}	18.2971
	K_{PD}	0.2059
PID controller of DC voltage	K_{DP}	195.1838
	K_{DI}	192.8871
	K_{DD}	0.2849
PID controller of bus voltage	K_{VP}	82.3538
	K_{VI}	290.7585
	K_{VD}	0.0560

Table 4. Optimum values of PI controller parameters using PSO.

PI controller of power flow	K_{PP}	4.1308
	K_{PI}	25.7369
PI controller of DC voltage	K_{DP}	149.9691
	K_{DI}	37.7309
PI controller of bus voltage	K_{VP}	141.7293
	K_{VI}	0.01

Table 5. 10% step increase in the reference power of line 2 (P_{e2ref}).

	The calculated ITAE	
	PID	**PI**
Nominal operating condition	2.5563×10^{-4}	4.4789×10^{-4}
Heavy operating condition	2.7744×10^{-4}	4.8698×10^{-4}

under system uncertainties (controller robustness), two operating conditions are considered as follow:

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

The parameters for these two scenarios are presented in appendix. It should be noted that PID 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 10% step change in the reference power of line 2 (Pe2ref) at all operating conditions (Nominal and Heavy) and results are listed at Table 5. Following step change, the PID controllers has better performance than PI controllers at all operating conditions. It is clearly seen that PID controller shows a more robust performance than PI controller at all operating conditions. With changing system operating condition, the PID controller can mitigate oscillations with acceptable time domain characteristics. This performance of PID controllers is due to its damping characteristics which are for the sake of differential section of it.

Also simulation results following 0.1 step change in the reference power of line 2 (Pe2ref) in the nominal operating condition are shown in Figures 7- 10. Figure 7 shows the power of line 2 changes from zero to 0.1 after 0.1 step change in the reference power of line 2; therefore UPFC successfully alters the power flow of line 2 based on the command reference. Figure 8 shows that the DC voltage of UPFC goes back to zero after disturbances and the steady state error has been removed and Figure 9 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. Figure 10 shows

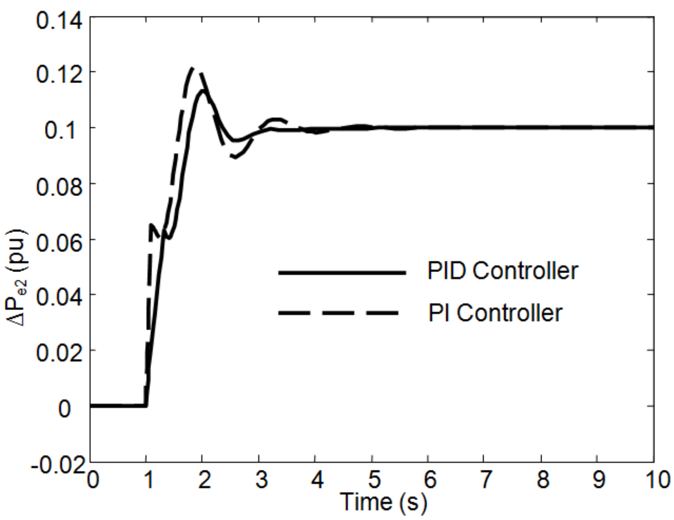

Figure 7. Dynamic response ΔP_{e2} following 10% step change in the reference power of line 2.

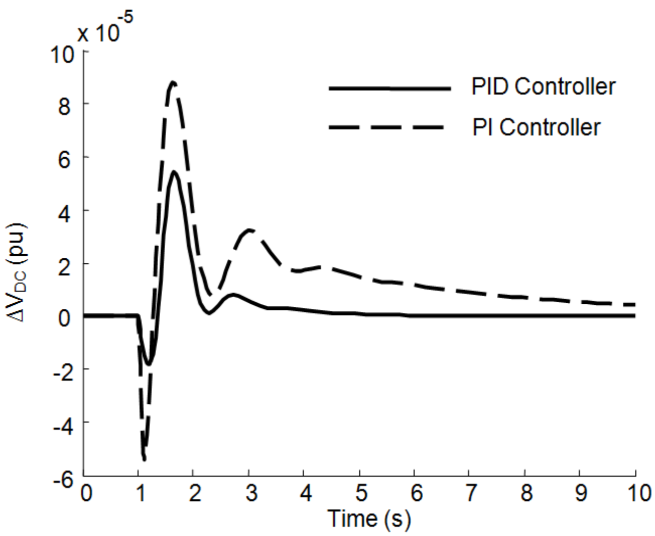

Figure 8. Dynamic response ΔV_{DC} following 10% step change in the reference power of line 2.

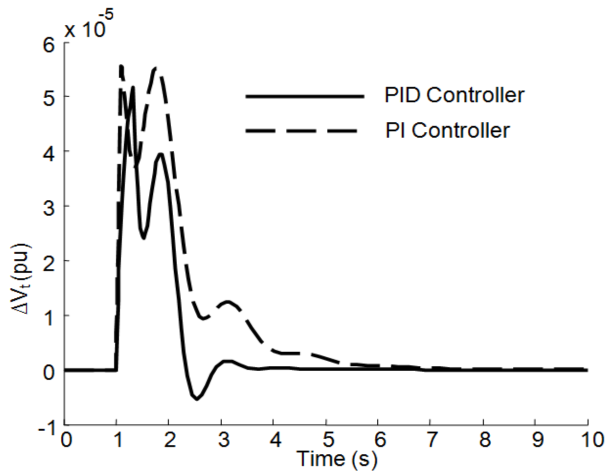

Figure 9. Dynamic response ΔV_t following 10% step change in the reference power of line 2.

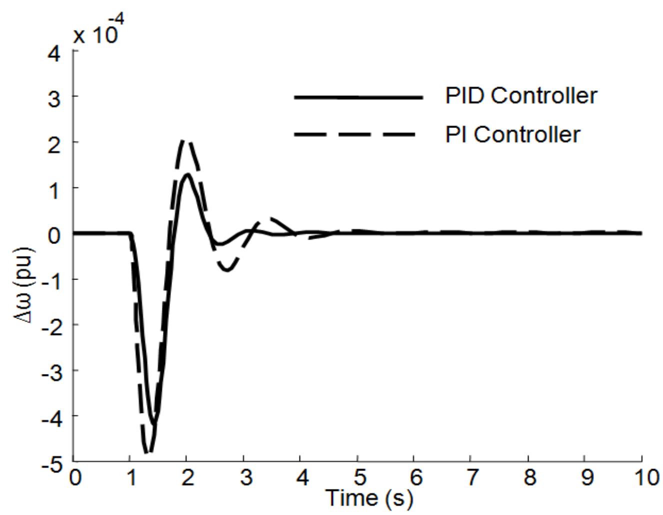

Figure 10. Dynamic response $\Delta\omega$ following 10% step change in the reference power of line 2.

the deviation of synchronous speed and it is seen that the supplementary stabilizer greatly enhances damping of oscillations and therefore the system becomes more stable and robust. In all cases, the PID controllers have better performance than PI controllers in control of power system and also stability enhancement.

Conclusions

In this paper, UPFC was successfully considered in order to simultaneously control power flow, bus voltage and DC voltage and also a stabilizer supplementary controller based UPFC incorporated for damping power system oscillations. Internal UPFC controllers modeled as PID type and their parameters were tuned using PSO. The simulation results showed that the UPFC with PID controllers has better performance in power system control and stability enhancement than UPFC with PI controllers. The multi objective abilities of UPFC in control and stability were successfully showed by time domain simulations.

ACKNOWLEDGMENT

This paper is a result of an approved research project in Islamic Azad University Boroujen branch, therefore we know necessary to thank this academic unit staunch for its most grateful support.

REFERENCES

Alasooly H, Redha M (2010). Optimal control of UPFC for load flow control and voltage flicker elimination and current harmonics elimination. Computers and Math with App., 60: 926-943.

Al-Awami A (2007). A Particle-Swarm based approach of power system stability enhancement with UPFC. Electr. Power Energy Syst., 29: 251-259.

Eldamaty AA, Faried SO, Aboreshaid S (2005). Damping power system oscillation using a Fuzzy logic based Unified Power Flow Controller. IEEE CCGEI., 1: 1950-1953.

Faried SO, Billinton R (2009). Probabilistic technique for sizing FACTS devices for steady-state voltage profile enhancement. IET Gen., Trans. Dist., 3: 385-392.

Guo J, Crow ML (2009). An improved UPFC control for oscillation damping. IEEE Trans. Power Syst., 25: 288 – 296.

Heffron WG, Phillips RA (1952). Effect of a modern voltage regulator on underexcited operation of large turbine generators. AIEE Trans., 71: 692–697.

Hingorani NG, Gyugyi L (2000). Understanding FACTS, IEEE Press, pp., 323-387.

Jiang S, Gole AM, Annakkage UD, Jacobson DA (2010). Damping Performance Analysis of IPFC and UPFC Controllers Using Validated Small-Signal Models. IEEE Trans. Power Deliv., 26: 446-454.

Jiang X, Chow JH, Edris A, Fardanesh B (2010). Transfer path stability enhancement by voltage-sourced converter-based FACTS controllers. IEEE Trans. Power Deliv., 25: 1019–1025.

Mehraeen S, Jagannathan S, Crow ML (2010). Novel Dynamic Representation and Control of Power Systems with FACTS Devices. IEEE Trans. Power Syst., 25: 1542-1554.

Nabavi-Niaki A, Iravani MR (1996). Steady-state and dynamic models of Unified Power Flow Controller for power system studies. IEEE Trans. Power Syst., 11: 1937-1950.

Randy LH, Sue EH (2004). Practical Genetic Algorithms, Second Edition, John Wiley & Sons, pp. 51-65.

Taher SA, Hematti R, Abdolalipor A (2008). Low frequency oscillation damping by UPFC with a robust Fuzzy supplementary controller. Int. J. Electr. Power Eng., 2: 314-320.

Tambey N, Kothari ML (2003). Damping of power system oscillation with Unified Power Flow Controller. IEE Proc. Gene. Trans. Dist., 150: 129-140.

Wang HF (2000). A unified model for the analysis of FACTS devices in damping power system oscillation Part III: Unified Power Flow Controller. IEEE Trans. Power Deliv., 15: 978-983.

Wang HF (1999). Damping Function of UPFC. IEE Proc. Gen. Trans. Dist., 146: 129-140.

Yu NY (1983). Electric power system dynamics. Academic Press, London, pp. 41-115.

Zarghami M, Crow ML, Sarangapani J, Yilu Liu, Atcitty S (2010). A novel approach to inter-area oscillations damping by UPFC utilizing ultra-capacitors. IEEE Trans. Power Syst., 25: 404–412.

APPENDIX

The nominal system parameters are listed in Table 6. Also system operating conditions are defined as Table 7 (Operating condition 1 is the nominal operating condition).

Table 6. System parameters.

Generator	T'_{do} = 5.044 s, X'_d = 0.3 p.u., X_d = 1 p.u., X_q = 0.6 p.u., M = 8 Mj/MVA	
Excitation system	Ka = 10	Ta = 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 = 1.0307 δ_E =32.57°	m_B = 0.1347 δ_B = -8.0173°

Table 7. System operating conditions.

Operating condition 1	P = 1 p.u.	Q = 0.2 p.u.
Operating condition 2	P = 1.1 p.u.	Q = 0.25 p.u.