

Full Length Research Paper

UPFC supplementary stabilizer controller design using optimization methods

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This paper presents the application of Unified Power Flow Controller (UPFC) to enhance damping of Low Frequency Oscillations (LFO) at a Single-Machine Infinite-Bus (SMIB) power system installed with UPFC. Since UPFC is considered to mitigate LFO, therefore a supplementary damping controller based UPFC like power system stabilizer is designed to reach the defined purpose. Optimization methods such as Particle Swarm Optimization (PSO) and Genetic Algorithms (GA) are considered to design UPFC supplementary stabilizer controller. To show effectiveness and also comparing these two methods, the proposed methods are simulated under different operating conditions. Several linear time-domain simulation tests visibly show the validity of proposed methods in damping of power system oscillations. Also simulation results emphasis on the better performance of PSO in comparison with GA method.

Key words: Flexible AC transmission systems, unified power flow controller, low frequency oscillations, particle swarm optimization, genetic algorithms.

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 Gyugyi, 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. Also, the UPFC can be used for voltage support and transient stability improvement by damping of low frequency power system oscillations (Gyugyi, 1992; Gyugyi, 1995; Bhowmick et al., 2008; Faried and Billinton, 2009; Jiang et al., 2010). 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

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Abbreviations: ITAE, Time multiplied absolute value of the error; PSO, particle swarm optimization; PSS, power system stabilizers; PWM, pulse width modulation; SMIB, Sigel machine infinite bus; LFO, low frequency oscillations; FACTS, flexible AC transmission system; GA, genetic algorithms; UPFC, unified power flow controller; IEEE – ST1A, Institute of Electrical and Electronics Engineers-Standard 1A.

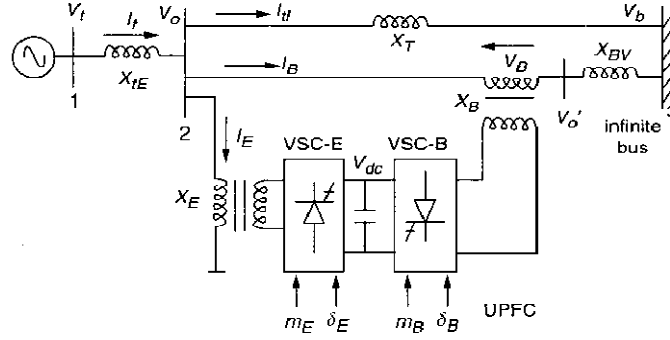


Figure 1. A Single Machine Infinite Bus (SMIB) power system installed with UPFC.

presented lead-Lag type UPFC damping controllers (Wang, 1999; Tambey and Kothari, 2003; Guo and Crow, 2009; Zarghami et al., 2010). 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 (Eldamaty et al., 2005; Al-Awami, 2007; Taher and Hematti, 2008; Taher et al., 2008) offer better dynamic performances than fixed parameter controllers.

The objective of this paper is to investigate the ability of optimization methods such as Genetic Algorithms (GA) and Particle Swarm Optimization (PSO) for UPFC supplementary stabilizer controller design. A Sigel machine infinite bus (SMIB) power system installed with a UPFC is considered as case study and a UPFC based stabilizer controller whose parameters are tuned using PSO and GA is considered as power system stabilizer. Different load conditions are considered to show effectiveness of the proposed methods and also comparing the performance of these two methods. Simulation results show the validity of proposed methods in LFO damping.

SYSTEM UNDER STUDY

Figure 1 shows a SMIB power system installed with UPFC (Hingorani and Gyugyi, 2000). 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 static excitation system, model type IEEE – ST1A, has been considered. The UPFC is assumed to be based on pulse width modulation (PWM) converters. The nominal system parameters are given in Appendix (Table 5).

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 Iravani, 1996; Wang, 2000). The nonlinear

dynamic model of the system installed with UPFC is given in Equation (1):

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

The equation for real power balance between the series and shunt converters is given in Equation (2):

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

Linear dynamic model

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

$$\begin{cases} \Delta\dot{\delta} = w_0\Delta w \\ \Delta\dot{\omega} = (-\Delta P_e - D\Delta\Delta)/M \\ \Delta\dot{E}'_q = (-\Delta E_q + \Delta E_{fd})/T'_{do} \\ \Delta\dot{E}'_{fd} = \frac{1}{T_a}\Delta E_{fd} - \frac{K_a}{T_a}\Delta V \\ \Delta\dot{V}_{dc} = K_7\Delta\delta + K_8\Delta E'_q - K_9\Delta V_{dc} + K_{ce}\Delta m_E + K_{cs\delta}\Delta\delta + K_{cv}\Delta m_B + K_{cs\delta}\Delta\delta \end{cases} \quad (3)$$

Where:

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

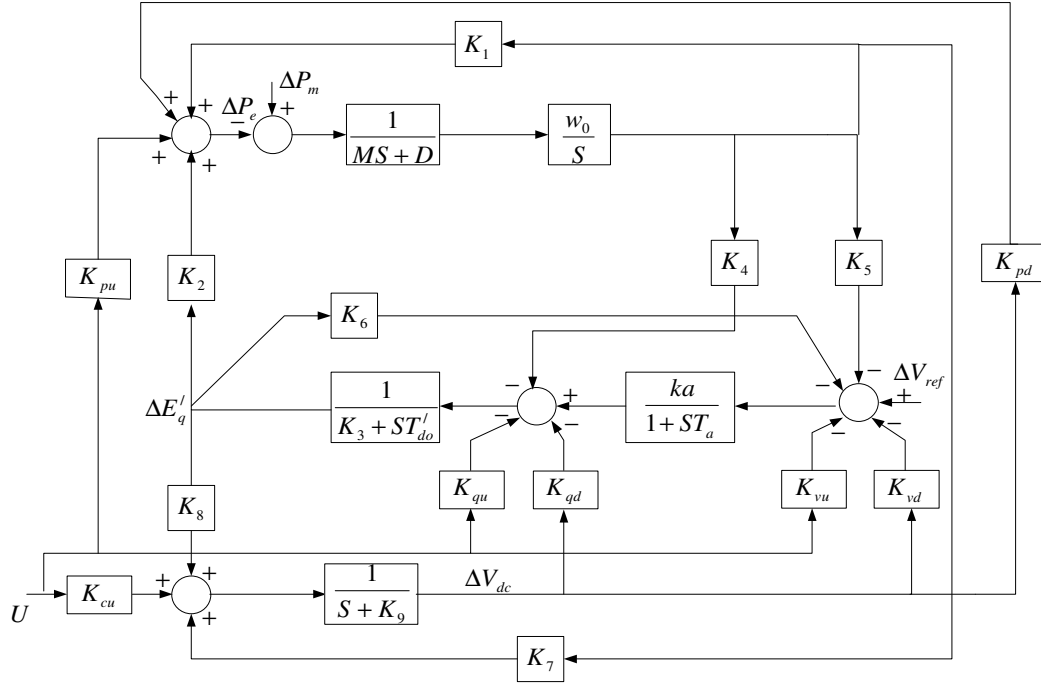


Figure 2. Transfer function model of the system including UPFC.

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

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

Where:

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

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

Δm_E : Deviation in pulse width modulation index m_E of shunt inverter. By controlling m_E , the output voltage of the shunt converter is controlled.

$\Delta \delta_E$: Deviation in phase angle of the shunt inverter voltage.

The series and shunt converters are controlled in a coordinated manner to ensure that the real power output of the shunt converter is equal to the power input to the series converter. The fact that the DC-voltage remains constant ensures that this equality is maintained.

It should be noted that K_{pu} , K_{qu} , K_{vu} and K_{cu} as shown in Figure 2 are the row vectors and defined as follow:

$$K_{pu} = [K_{pe} \quad K_{pde} \quad K_{pb} \quad K_{p\delta b}]; \quad K_{qu} = [K_{qe} \quad K_{qde} \quad K_{qb} \quad K_{q\delta b}]$$

$$K_{vu} = [K_{ve} \quad K_{vde} \quad K_{vb} \quad K_{v\delta b}]; \quad K_{cu} = [K_{ce} \quad K_{cde} \quad K_{cb} \quad K_{c\delta b}]$$

Dynamic model in state-space form

The dynamic model of the system in state-space form is given in Equation (5):

$$\begin{bmatrix} \Delta \delta \\ \Delta \omega \\ \Delta E'_q \\ \Delta E'_{fd} \\ \Delta V_{dc} \end{bmatrix} = \begin{bmatrix} 0 & w_0 & 0 & 0 & 0 \\ -\frac{K_1}{M} & 0 & \frac{K_2}{M} & 0 & \frac{K_{pd}}{M} \\ \frac{K_4}{K_3 + ST'_{do}} & 0 & \frac{K_5}{K_3 + ST'_{do}} & \frac{1}{1 + ST_a} & \frac{K_{qd}}{K_3 + ST'_{do}} \\ \frac{K_{qu}}{K_A K_S} & 0 & \frac{K_{qu}}{K_A K_S} & \frac{1}{T_A} & \frac{K_{qu}}{K_A K_S} \\ \frac{K_7}{K_8} & 0 & \frac{K_8}{K_8} & 0 & -K_9 \end{bmatrix} \times \begin{bmatrix} \Delta \delta \\ \Delta \omega \\ \Delta E'_q \\ \Delta E'_{fd} \\ \Delta V_{dc} \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 & 0 \\ \frac{K_{pe}}{M} & \frac{K_{pde}}{M} & \frac{K_{pb}}{M} & \frac{K_{p\delta b}}{M} \\ \frac{K_{qe}}{T'_{do}} & \frac{K_{qde}}{T'_{do}} & \frac{K_{qb}}{T'_{do}} & \frac{K_{q\delta b}}{T'_{do}} \\ \frac{K_{ve}}{T_A} & \frac{K_{vde}}{T_A} & \frac{K_{vb}}{T_A} & \frac{K_{v\delta b}}{T_A} \\ K_{ce} & K_{cde} & K_{cb} & K_{c\delta b} \end{bmatrix} \times \begin{bmatrix} \Delta m_E \\ \Delta \delta_E \\ \Delta m_B \\ \Delta \delta_B \end{bmatrix} \quad (5)$$

UPFC controllers

In this research two control strategies are considered for UPFC:

- i. DC-voltage regulator;
- ii. Power system oscillation-damping controller.

DC-voltage regulator

In UPFC, the output real power of the shunt converter must be equal to the input real power 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. In this paper a PI type controller is considered to be in control of the DC voltage. The parameters of this PI type DC-voltage regulator are considered as $K_I=39.5$ and $K_P=6.54$.

Power system oscillations-damping controller

A stabilizer controller is provided to improve damping of power system oscillations. This controller may be considered as a lead-lag

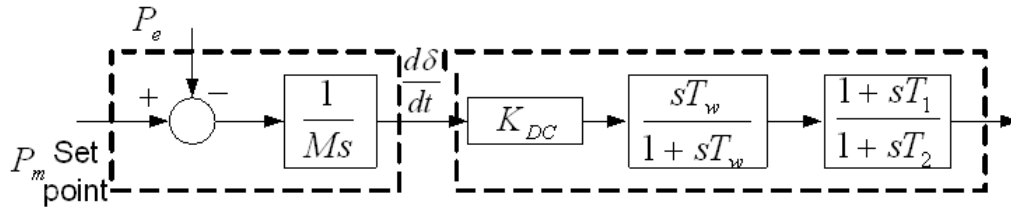


Figure 3. The structure of damping controller.

Table 1. Eigen-values of the closed-loop system without damping controller.

Eigen-values	-15.3583
	-5.9138
	0.7542 + 3.3055i
	0.7542 - 3.3055i
	-0.7669

compensator. However, an electrical torque in phase with the speed deviation should be produced to improve damping of power system oscillations. The transfer function model of the stabilizer controller is shown in Figure 3.

ANALYSIS

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

Stabilizer controllers design themselves have been a topic of interest for decades, especially in form of Power System Stabilizers (PSS) (Wang, 1999; Tambey and Kothari, 2003; Eldamaty et al., 2005; Al-Awami, 2007; Taher and Hematti, 2008; Taher et al., 2008; Guo and Crow, 2009; Zarghami et al., 2010). But PSS cannot control power transmission and also can not support power system stability under large disturbances like 3-phase fault at terminals of generator (Mahran et al., 1992). For these problems, in this paper a stabilizer controller based UPFC is provided to mitigate power system oscillations. Two optimization methods such as PSO and GA are considered for tuning stabilizer controller parameters. An introduction about particle swarm optimization (PSO) is presented.

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 (6)

and (7) (Randy and Sue, 2004)~:

$$V_{m,n}^{new} = w \times V_{m,n}^{old} + \Gamma_1 \times r_1 \times (P_{m,n}^{local\ best} - P_{m,n}^{old}) + \Gamma_2 \times r_2 \times (P_{m,n}^{global\ best} - P_{m,n}^{old}) \tag{6}$$

$$P_{m,n}^{new} = P_{m,n}^{old} + \Gamma V_{m,n}^{new} \tag{7}$$

Where: $V_{m,n}$ = particle velocity; $P_{m,n}$ = particle variables; W = inertia weight; r_1, r_2 = independent uniform random numbers; $\Gamma_1 = \Gamma_2$ = learning factors; $P_{m,n}^{local\ best}$ = best local solution; $P_{m,n}^{global\ best}$ = 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 minimizes 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).

Stabilizer controller design using PSO

In this section the parameters of the proposed stabilizer controller are tuned using PSO. Four control parameters of the UPFC (m_E, δ_E, m_B and δ_B) can be modulated in order to produce the damping torque. The parameter m_E is modulated to output of damping controller and speed deviation $\Delta\omega$ is also considered as input of damping controller. The structure of supplementary stabilizer controller has been shown in Figure 3. The parameters in Figure 3 are as follow: K_{DC} : the damping controller gain T_w :the parameter of washout block T_1 and T_2 : the parameters of compensation block The optimum values of K_{DC}, T_1 and T_2 which minimize an array of different performance indexes are accurately computed using PSO and T_w is considered equal to 10. In optimization methods, the first

Table 2. Optimum values of stabilizer controller parameters using PSO.

Value	Parameter		
	K_{DC}	T_1	T_2
	549.05	0.2187	0.01

Table 3. Optimum values of stabilizer controller parameters using GA.

Value	Parameter		
	K_{DC}	T_1	T_2
	631.02	0.251	0.1

Table 4. 10% Step increase in the reference torque (ΔT_m).

	The calculated ITAE	
	PSO Stabilizer	GA Stabilizer
Nominal operating condition	0.0018	0.002
Heavy operating condition	0.0019	0.0022

step is to define a performance index for optimal search. In this study the performance index is considered as Equation (8). In fact, the performance index is the integral of the time multiplied absolute value of the error (*ITAE*).

$$ITAE = \int_0^t |\Delta\omega| dt + \int_0^t |\Delta V_{DC}| dt \quad (8)$$

Where, $\Delta\omega$ is the frequency deviation, ΔV_{DC} is the deviation of DC voltage 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 (ΔT_m) is assumed and the performance index is minimized using PSO. In order to acquire better performance, number of particle, particle size, number of iteration, Γ_1 , Γ_2 , and Γ are chosen as 24, 3, 50, 2, 2 and 1, respectively. Also, the inertia weight, w , is linearly decreasing from 0.9 to 0.4. The optimum values of K_{DC} , T_1 and T_2 , resulting from minimizing the performance index is presented in Table 2. Also in order to show effectiveness of PSO method, the parameters of stabilizer controller are tuned using the other optimization method, GA. In GA case, the performance index is considered as PSO case and the optimal parameters of stabilizer controller are obtained as shown in Table 3. In this paper the boundaries of parameters are defined as follows: $1 < K_{DC} < 100$, $0.01 < T_1$ and $T_2 < 1$.

SIMULATION RESULTS

In this section, the designed PSO and GA based stabilizer controllers are applied to damping LFO in the understudy system. In order to study and analysis system performance under system uncertainties (controller robustness), two operating conditions are considered as

follow: Case 1: Nominal operating condition Case 2: Heavy operating condition The parameters for two cases are presented in Appendix (Table 6). PSO and GA stabilizer controllers have been designed for the nominal operating condition. In order to demonstrate the robustness performance of the proposed method, the *ITAE* is calculated following 10% step change in the reference torque (ΔT_m) at all operating conditions (Nominal and Heavy) and results are shown in Tables 4. Following step change, the PSO based stabilizer has better performance than the GA based stabilizer at all operating conditions. Also for case 1 the simulation results are shown in Figures 4 and 5. The simulation results show that applying the supplementary control signal greatly enhances the damping of the generator angle oscillations and therefore the system becomes more stable. The PSO stabilizer performs better than the GA controller. For case 2, the simulation results are shown in Figures 6 and 7. Under this condition, while the performance of GA supplementary controller becomes poor, the PSO controller has a stable and robust performance. It can be concluded that the PSO supplementary controller have suitable parameter adaptation in comparing with the GA supplementary controller when operating condition changes.

Conclusions

In this paper genetic algorithms and particle swarm optimization have been successfully applied to design stabilizer controller based UPFC. A single machine

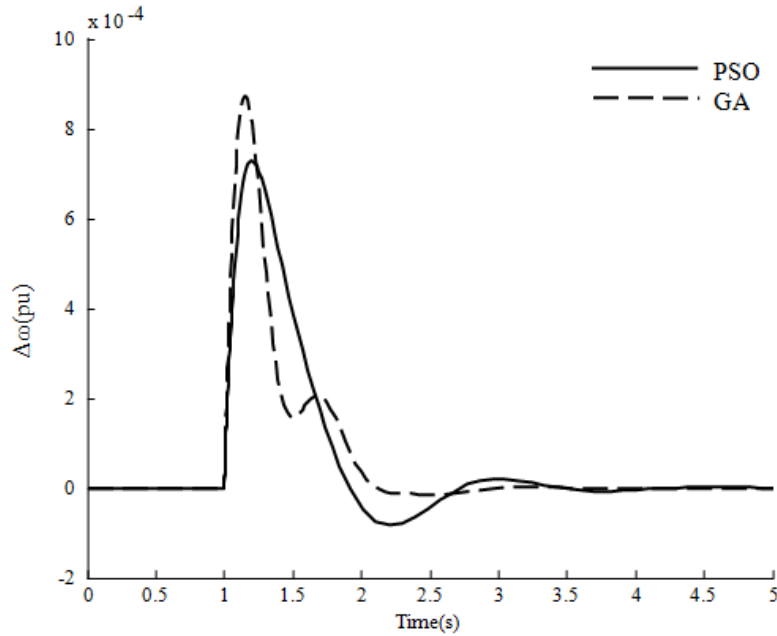


Figure 4. Dynamic response $\Delta\omega$ for case 1.

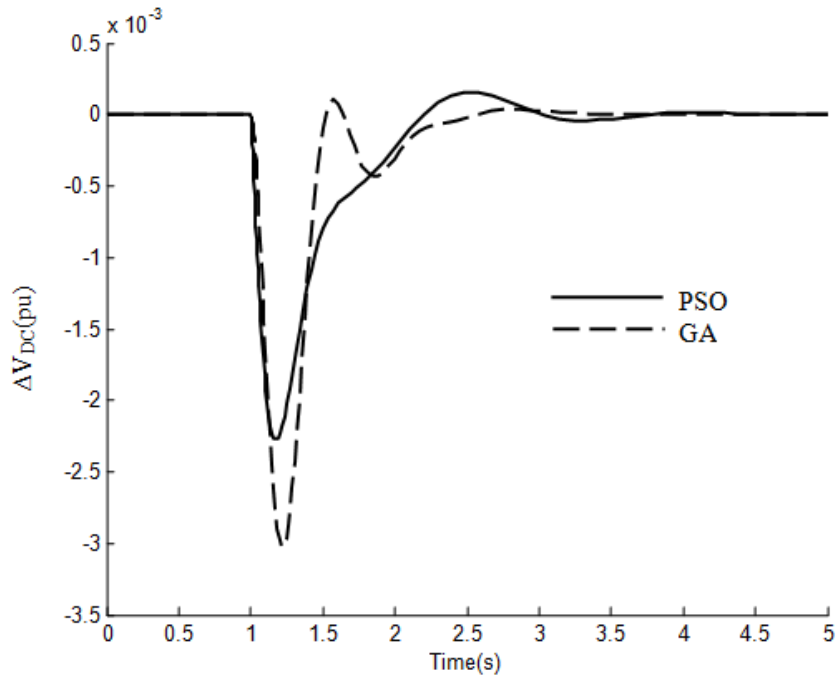


Figure 5. Dynamic response ΔV_{DC} for case 1.

infinite bus power system installed with a UPFC with various load conditions has been assumed to demonstrate the methods. Simulation results demonstrated that the designed controllers capable to guarantee the robust

stability and robust performance under a different load conditions. Also, simulation results show that the PSO method has an excellent capability in power system oscillations damping and power system stability

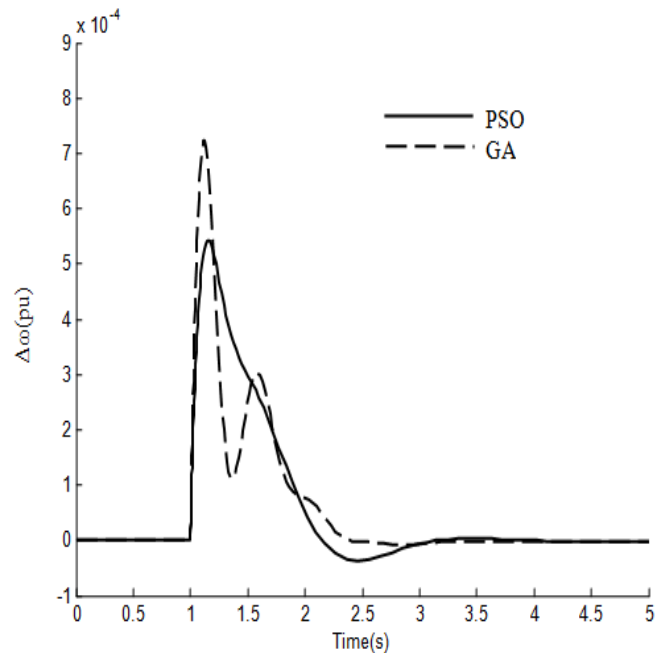


Figure 6. Dynamic response $\Delta\omega$ for case 2.

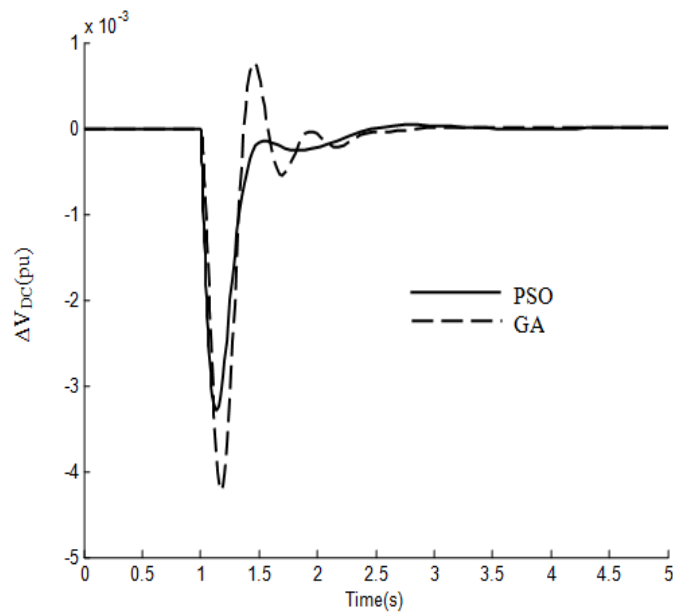


Figure 7. Dynamic response ΔV_{DC} for case 2.

enhancement under small disturbances in comparison with GA method.

REFERENCES

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

Bhowmick S, Das B, Kumar N (2008). An indirect UPFC model to enhance reusability of Newton power-flow codes, *IEEE Trans. Power Delivery*, 23(4): 2079 – 2088.

Eldamaty AA, Faried SO, Aboreshaid S (2005). Damping power syst. 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 enhance. *IET gen. trans. dist.*, 3(4): 385 – 392.

Gyugyi L (1992). Unified Power Flow Control concept for Flexible AC

- Transmission Syst. IEEE Proc., 139(4): 323-331.
- Gyugyi L (1995). The UPFC: A new approach to power trans. control, IEEE Trans. Power Delivery, 10(2): 1085-1093.
- Guo J, Crow ML (2009). An improved UPFC control for oscillation damping, IEEE Trans. Power Syst., 25(1): 288-296.
- Hingorani NG, Gyugyi L (2000). Understanding FACTS, IEEE Press. 2000.
- 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 Delivery, 26(1): 446-454.
- Mahran AR, Hogg BW, El-sayed ML (1992). Co-ordinate control of synchronous generator excitation and static var compensator, IEEE Trans. Energy Convers., 7(4): 615-622.
- 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(4): 1937-1950.
- Randy LH, Sue EH (2004). Practical Genetic Algorithms, Second Edition, John Wiley & Sons.
- Taher SA, Hematti R (2008). Optimal supplement. controller designs using GA for UPFC in order to LFO damping. Int. J. Soft Comp., 3(5): 382-389.
- Taher SA, Hematti R, Abdolalipor A (2008). Low frequency oscillation damping by UPFC with a robust Fuzzy supplement controller. Int. J. Elec. Power Eng., 2: 314-320.
- Tambey N, Kothari ML (2003). Damping of power syst. oscillation with Unified Power Flow Controller, IEE Proc. Gene. Trans. Dist., 150(2): 129-140.
- Wang HF (1999). Damping Function of UPFC, IEEE Proc. Gen. Trans. Dist., 146(1): 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(3): 978-983.
- Zarghami M, Crow ML, Sarangapani J, Yilu L, Atcity S (2010). A novel approach to inter-area oscillations damping by UPFC utilizing ultra-capacitors, IEEE Trans. Power Syst., 25(1): 404 – 412.

APPENDIX

The nominal parameters and nominal operating condition of the system are listed in Table 5. Also system operating conditions are defined as shown in Table 6 (Operating condition 1 is the nominal operating condition).

Table 5. System parameters.

Generator	$M = 8 \text{ Mj/MVA}$ $X_q = 0.6 \text{ p.u.}$	$T'_{do} = 5.044 \text{ s}$ $X'd = 0.3 \text{ p.u.}$	$X_d = 1 \text{ p.u.}$ $D = 0$
Excitation system		$K_a = 10$	$T_a = 0.05 \text{ s}$
Transformers		$X_{te} = 0.1 \text{ p.u.}$	$X_{SDT} = 0.1 \text{ p.u.}$
Transmission lines		$X_{T1} = 1 \text{ p.u.}$	$X_{T2} = 1.25 \text{ p.u.}$
Operating condition	$V_t = 1.03 \text{ p.u.}$	$P = 0.9 \text{ p.u.}$	$Q = 0.2 \text{ p.u.}$
DC link parameters		$V_{DC} = 2 \text{ p.u.}$	$C_{DC} = 3 \text{ p.u.}$
UPFC parameters		$m_E = 1.0224$ $\delta_E = 22.24^\circ$	$m_B = 0.142$ $\delta_B = -48.61^\circ$

Table 6. System operating conditions.

	P (p.u.)	Q (p.u.)	V_t (p.u.)
Operating condition 1	1	0.2	1.03
Operating condition 2	1.05	0.35	1.03