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STATCOM Control using a PSO-Based IP Controller

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Abstract: This study presents the application of static synchronous compensator (STATCOM) in order to simultaneous voltage support and damping of Low Frequency Oscillations (LFO) at a Single-Machine Infinite-Bus (SMIB) power system installed with STATCOM. PI (Proportional-Integral) type controllers are commonly used controllers for STATCOM control. But due to some drawbacks of PI type controllers, the scope for finding a better control scheme still remains. Concerning this problem, in this study the new IP (Integral-Proportional) type controllers are considered as STATCOM controllers. The parameters of these IP type controllers are tuned using Particle Swarm Optimization (PSO). Also a stabilizer supplementary stabilizer based on STATCOM is incorporated for increasing damping of power system oscillations. 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.

Key words: IP controller, low frequency oscillations, particle swarm optimization, static synchronous compensator, voltage control

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 *et al*., 2000). The static synchronous compensator (STATCOM) is one of the most important FACTS devices and it is based on the principle that a voltage-source inverter generates a controllable AC voltage source behind a transformer-leakage reactance so that the voltage difference across the reactance produces active and reactive power exchange between the STATCOM and the transmission network. The STATCOM is one of the important 'FACTS' devices and can be used for dynamic compensation of power systems to provide voltage support and stability improvement (Gyugyi *et al*., 1990; Gyugyi, 1979; Schauder *et al*., 1993; Schauder *et al*., 1995; Ekanayake *et al*., 1995; Saad-Saoud *et al*., 1998; Trainner *et al*., 1994; Ainsworth *et al*., 1998; Mori *et al*., 1993). In Wang *et al.* (1999) a unified Phillips-Heffron model (Heffron *et al*., 1952) of power systems installed with a STATCOM is established. Also STATCOM can be used for transient stability improvement by damping of low frequency power system oscillations (Tambey *et al.*, 2003; Cheng *et al*., 1986; Al-Awami *et al*., 2007; Mishra *et al*., 2000; Eldamaty *et al*., 2005).

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

METHODOLOGY

Illustrative test: Figure 1 shows the case study system in this paper. The system is a Single Machine Infinite Bus (SMIB) power system with STATCOM installed.

Nonlinear model of the system: A non-linear dynamic model of the system is derived by disregarding the resistances of all components of the system (generator, transformer, transmission line and shunt converter transformer) and the transients of the transmission lines and transformer of the STATCOM. The nonlinear dynamic model is given as (1) (Wang *et al.*, 1999):

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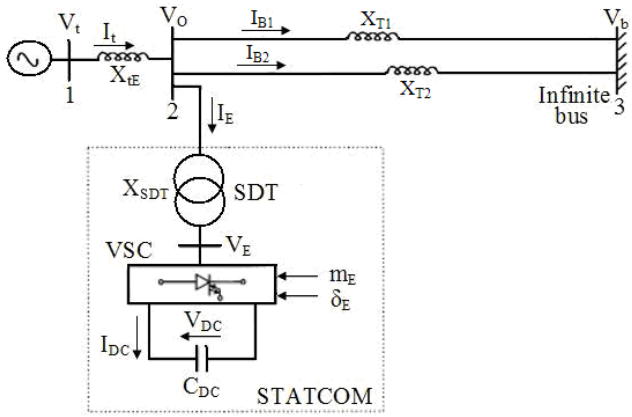

Fig. 1: A single-machine infinite-bus power system installed with STATCOM

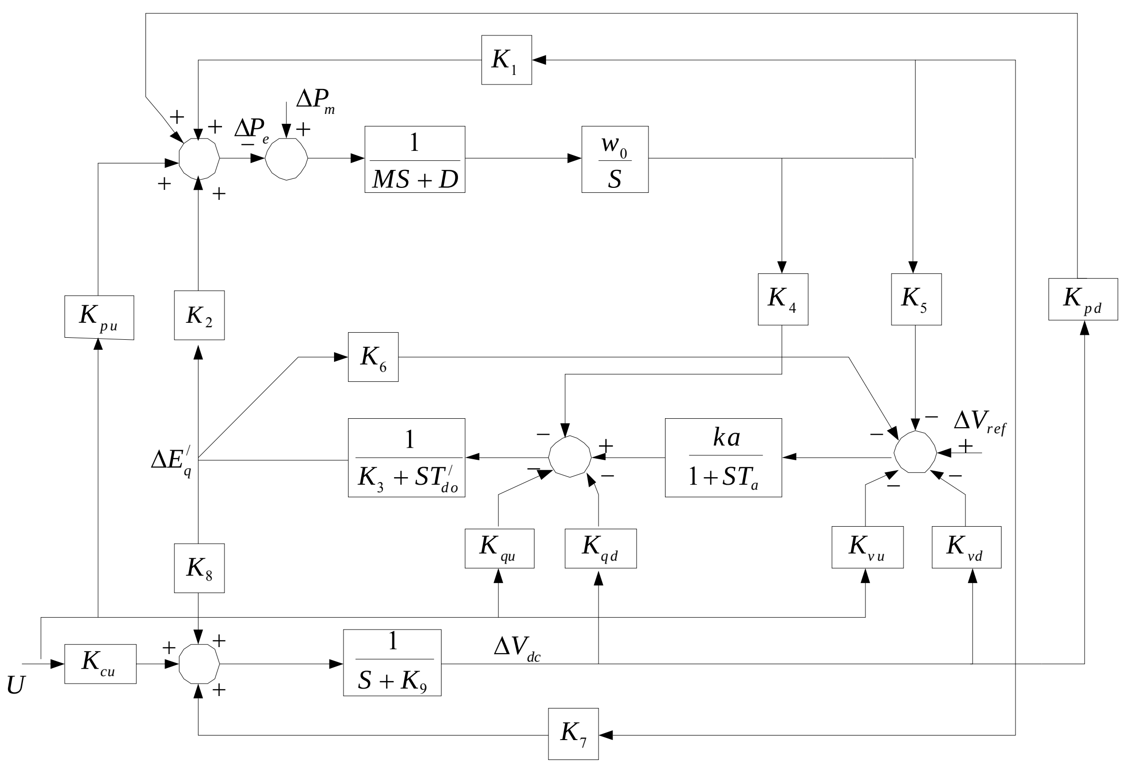

Fig. 2: Transfer function model of the system including STATCOM

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

Linear model: A linear dynamic model is obtained by linearising the non-linear model around the nominal operating condition. The linearised model is given as (2):

$$\begin{cases} \Delta\dot{\delta} = w_0 \Delta w \\ \Delta\dot{\omega} = (-\Delta P_e - D\Delta\omega) / M \\ \Delta\dot{E}_q^/ = (-\Delta E_q + \Delta E_{fd}) / T_{do}^/ \\ \Delta\dot{E}_{fd} = -(1/T_A)\Delta E_{fd} - (K_A / T_A)\Delta V_t \\ \Delta\dot{v}_{dc} = K_7\Delta\delta + K_8\Delta E_q^/ - K_9\Delta v_{dc} + K_{ce}\Delta m_E \\ \qquad + K_{c\delta e}\Delta\delta_E \end{cases} \quad (2)$$

where,

$$\Delta P_e = K_1\Delta\delta + K_2\Delta E_q^{/} + K_{pd}\Delta v_{dc} + K_{pe}\Delta m_E + K_{p\delta E}\Delta\delta_E$$
$$\Delta E_q = K_4\Delta\delta + K_3\Delta E_q^{/} + K_{qd}\Delta v_{dc} + K_{qe}\Delta m_E + K_{q\delta E}\Delta\delta_E$$
$$\Delta V_t = K_5\Delta\delta + K_6\Delta E_q^{/} + K_{vd}\Delta v_{dc} + K_{ve}\Delta m_E + K_{v\delta E}\Delta\delta_E$$

Figure 2 shows the transfer function model of the system including STATCOM. The model has constant parameters which are denoted by K_{ij}. These constant parameters are function of the system parameters and the initial operating condition. The control vector U in Fig. 2 is defined as (3):

$$U = [\Delta m_E \quad \Delta\delta_E]^T \tag{3}$$

where,

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

Δd_E : Deviation in phase angle of the shunt inverter voltage. By controlling δ_E, exchanging active power between the STATCOM and the power system is controlled

It should be noted that K_{pu}, K_{qu}, K_{vu} and K_{cu} in Fig. 2 are the row vectors and defined as follows:

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

The dynamic model of the system in state-space form is obtained as (4). The typical values of system parameters for the nominal operating condition are given in Appendix.

$$\begin{bmatrix}\Delta\dot\delta \\ \Delta\dot w \\ \Delta\dot E_q^{/} \\ \Delta\dot E_{fd} \\ \Delta\dot v_{dc}\end{bmatrix} = \begin{bmatrix} 0 & w_0 & 0 & 0 & 0 \\ -\frac{K_1}{M} & 0 & -\frac{K_2}{M} & 0 & -\frac{K_{pd}}{M} \\ -\frac{K_4}{T_{do}^{/}} & 0 & \frac{K_3}{T_{do}^{/}} & -\frac{1}{T_{do}^{/}} & -\frac{K_{qp}}{T_{do}^{/}} \\ -\frac{K_A K_5}{T_A} & 0 & -\frac{K_A K_6}{T_A} & -\frac{1}{T_A} & \frac{K_A K_{vd}}{T_A} \\ K_7 & 0 & K_8 & 0 & -K_9 \end{bmatrix} \times \begin{bmatrix}\Delta\delta \\ \Delta w \\ \Delta E_q^{/} \\ \Delta E_{fd} \\ \Delta v_{dc}\end{bmatrix} + \begin{bmatrix} 0 & 0 \\ -\frac{K_{pe}}{M} & -\frac{K_{p\delta e}}{M} \\ -\frac{K_{qe}}{T_{do}^{/}} & -\frac{K_{q\delta e}}{T_{do}^{/}} \\ -\frac{K_A K_{ve}}{T_A} & -\frac{K_A K_{v\delta e}}{T_A} \\ Kce & K_{c\delta e} \end{bmatrix} \times \begin{bmatrix}\Delta m_E \\ \Delta\delta_E\end{bmatrix} \tag{4}$$

IP controller: As referred before, in this study IP type controllers are considered as STATCOM internal controllers. Figure 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 (Sul, 2011). 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 (Sul, 2011).

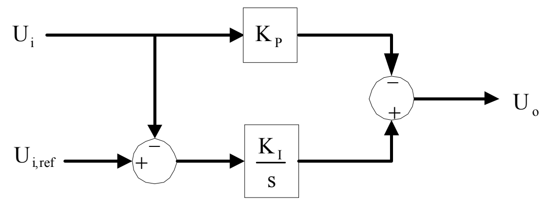

Fig. 3: Structure of the IP controller

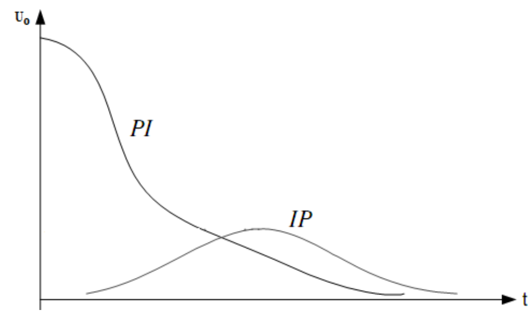

Fig. 4: Output of IP and PI regulators with the same damping coefficient and the same band width at the same step input signal command (Sul, 2011)

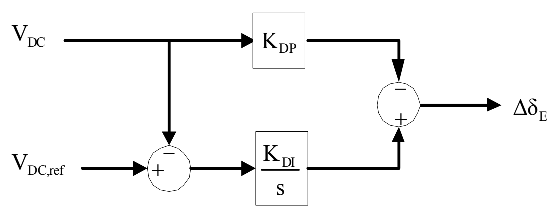

Fig. 5: DC-voltage regulator

STATCOM controllers: In this study three control strategies are considered for STATCOM:

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

Internal STATCOM controllers: STATCOM has two internal controllers which are Bus voltage controller and DC voltage regulator. In order to control of DC voltage, a DC-voltage regulator is incorporated. DC-voltage is

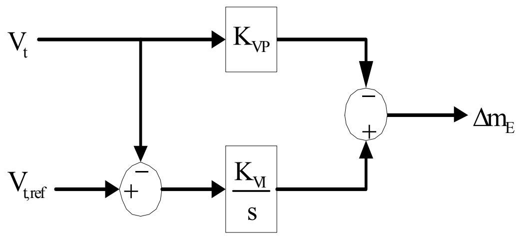

Fig 6. Generator terminals voltage controller

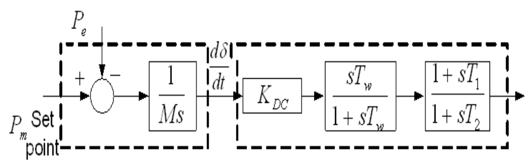

Fig 7. Stabilizer controller

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

-17.1146, +0.0213±3.711i, -0.5401±0.4991i

regulated by modulating the phase angle of the shunt converter voltage. Figure 5 shows the structure of the DC-voltage regulator. Also Fig. 6 shows the structure of the generator terminals voltage controller. The generator terminals voltage controller regulates the voltage of generator terminals during post fault in the system.

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. 7.

Analysis: For the nominal operating condition the eigen-values of the system are obtained using state-space model of the system presented in (4) 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.

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 two control parameters of the STATCOM (m_E and δ_E) can be modulated in order to produce the damping torque. In this study m_E is modulated in order to damping controller design also the speed deviation ω is considered as the input to the damping controllers. The structure of damping controller has been shown in Fig. 7. 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 by Kundur (1993). Damping controller has been designed and obtained as (5):

$$\text{Damping controlle} = \frac{481.3021 \;\; s\;(s+4.712)}{(s+0.1) \quad (s+5.225)} \tag{5}$$

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

-18.4188, -12.3155, -5.8812, -0.9251±0.9653, -0.8211±0.7903

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

Particle swarm optimization: PSO was formulated by Edward and Kennedy (1995). The thought process behind the algorithm was inspired by the social behavior of animals, such as bird flocking or fish schooling. PSO begins with a random population matrix. It has no evolution operators such as crossover and mutation. The rows in the matrix are called particles. 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 (6) and (7):

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

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

where, $V_{m,n}$: Particle velocity; $P_{m,n}$: Particle variables; W: Inertia weight; r_1, r_2: Independent uniform random numbers; Γ_1, Γ_2: Learning factors; Plocal bem,n $P_{m,n}^{local\,best}$: 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

Table 3: Optimum values of IP type controllers

IP controller of DC voltage	K_{DP}	9.6712
	K_{DI}	25.00
IP controller of bus voltage	K_{VP}	1.6908
	K_{VI}	31.821

Table 4: Optimum values of PI type controller

PI controller of DC voltage	K_{DP}	2.066
	K_{DI}	1.101
PI controller of bus voltage	K_{VP}	0.3201
	K_{VI}	33.812

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).

Controllers adjustment using PSO: In this section the parameters of the proposed IP type controllers are tuned using PSO. All two IP controllers are simultaneously tuned using PSO. In this study the performance index is considered as (8). In fact, the performance index is the Integral of the Time multiplied Absolute value of the Error (ITAE):

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

where, Δw is the frequency deviation, Δ_{VDC} is the deviation of DC voltage, ΔV_t is the deviation of bus 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 (ΔTm) 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 12, 4, 50, 2, 2 and 1, respectively. Also, the inertia weight, w, is linearly decreasing from 0.9 to 0.4. It should be noted that PSO algorithm is run several times and then optimal set of parameters is selected 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 STATCOM control and the parameters of these PI type controllers are tuned using PSO. The results are listed in Table 4.

RESULTS AND DISCUSSION

In order to evaluate the effectiveness of STATCOM and also comparing IP and PI type controllers, two operating conditions are considered as nominal and heavy operating conditions. The parameters for these two operating conditions are presented in the 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 mechanical torque (ΔTm) 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. The other important factor in the comparison of controllers is control effort signal. In this study following index is considered to compare of the IP and PI controllers.

Table 5: The calculated ITAE index for the both controllers

	IP	PI
Nominal operating condition	0.0102	0.0396
Heavy operating condition	0.0119	0.0419

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

	IP	PI
Nominal operating condition	2.041	2.0711
Heavy operating condition	2.162	2.1741

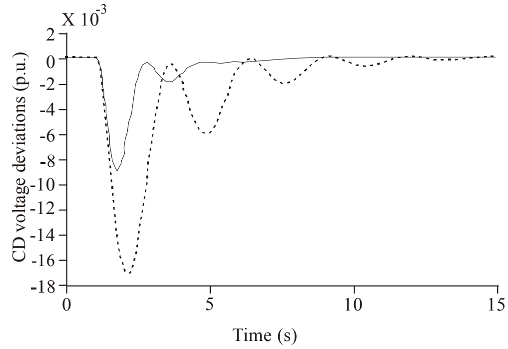

Fig. 8: Dynamic response DV_{DC} following 5% step change in the reference mechanical torque; Solid (IP controller); Dashed (PI controller)

$$\text{Control effort} = \int_0^t t|\Delta u|dt \quad (9)$$

where, u shows the control effort signal. The proposed metric 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 reference mechanical torque (ΔTm) in the heavy operating condition are shown in Fig. 8-10. Each figure contains to plots as solid for IP controller and dashed for PI controller. Figure 8 shows that the DC voltage of STATCOM goes back to zero after disturbances and the steady state error has been removed and Fig. 9 shows the

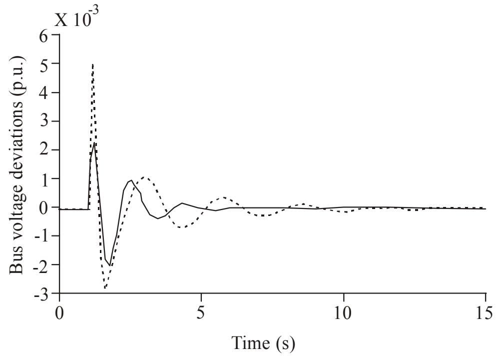

Fig. 9: Dynamic response DV_t following 5% step change in the reference mechanical torque; Solid (IP controller); Dashed (PI controller)

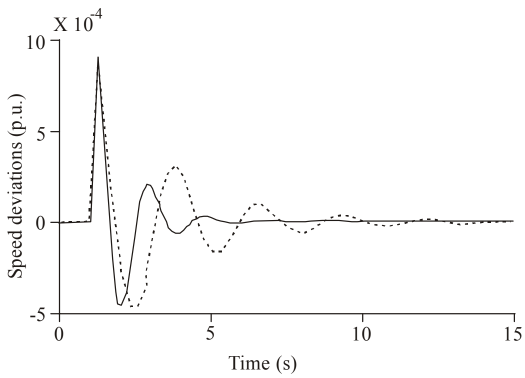

Fig. 10: Dynamic response $\Delta\omega$ following 5% step change in the reference mechanical torque; Solid (IP controller); Dashed (PI controller)

CONCLUSION

In this study STATCOM successfully incorporated in order to simultaneous control of bus voltage and DC voltage of generator's bus which is driven back to zero after oscillations. The results show that STATCOM can simultaneously control bus voltage and DC voltage. Figure 10 shows the deviation of synchronous speed and it is seen that the supplementary stabilizer greatly enhances the damping of the power system oscillations and thus the system becomes more stable and robust. In all cases, the IP method has better performance than PI in control of power system and also stability enhancement. voltage. Also a supplementary stabilizer based STATCOM incorporated for damping power system oscillations and stability enhancement. Internal STATCOM controllers modeled as IP type and their parameters tuned using PSO. The simulation results showed that the STATCOM with IP controllers has better performance in control and stability than STATCOM with PI controllers. The multi objective abilities of STATCOM in control and stability successfully were showed by time domain simulations.

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.
STATCOM parameters		M_e = 1.0224	δ_E = 22.24°

Table 8: System operating conditions

Operating condition 1	P = 1 p.u.	Q = 0.2 p.u.	V_t = 1.03 p.u.
Operating condition 2	P = 1.08 p.u.	Q = 0.25 p.u.	V_t = 1.03 p.u.

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REFERENCES

Ainsworth, J.D., M. Davies, J.B. Fitz, K.E. Owen and D.R. Trainer, 1998. Static var compensator (STATCOM) based on single-phase chain circuit converters. IEE P. Gener. Transm. D., 145(4): 381-386.

Al-Awami, A.T., 2007. A particle-swarm-based approach of power system stability enhancement with UPFC. Electrical Power Energ. Syst., 29: 251-259.

Cheng, S., O.P. Malik and S.G. Hope, 1986. Self-tuning stabilizers for a multi-machine power system. IEE Proc. Part C., 4: 176-185.

Ekanayake, J.B., N. Jenkins and C.B. Cooper, 1995. Experimental investigation of an advanced static var compensator. IEE P. Gener. Transm. D., 142(2): 202-210.

Eldamaty, A.A., S.O. Faried and S. Aboreshaid, 2005. Damping power system oscillation using a fuzzy logic based unified power flow controller. IEEE CCECE/CCGEI, 1: 1950-1953.

Gyugyi, L., 1979. Reactive power generation and control by thyristor circuits. IEEE Trans. IA., 15(5): 521-532.

Gyugyi, L., N.G. Hingorani, P.R. Nannery and T. Tai, 1990. Advanced Static Var compensator using Gate turn-off Thyristors for Utility Applications. The Proceedings of the 1990 CIGRE Conference, pp: 23-203.

Heffron, W.G. and R.A. Phillips, 1952. Effect of a modem amplidyne voltage regulator on under excited operation of large turbine generator. A IEE Trans., pp: 71-80.

Hingorani, N.G. and L. Gyugyi, 2000. Understanding FACTS. IEEE Press, New York.

Kundur, P., 1993. Power System Stability and Control. McGraw-Hill Inc., New York, pp: 700-822.

Mishra, S., P.K. Dash and G. Panda, 2000. TS-Fuzzy controller for upfc in a multi-machine power system. IEE P. Gener. Transm. D., 147(1): 15-22.

Mori, S., K. Matsuno, M. Takeda and M. Seto, 1993. Development of a large static var generator using self-commutated inverters for improving power system stability. IEEE Trans. Power Syst., 8(1): 371-377.

Randy, L.H. and E.H. Sue, 2004. Practical Genetic Algorithms. 2nd Edn., John Wiley and Sons.

Saad-Saoud, Z., M.L. Lisboa, J.B.E. Kanayake, N. Jenkins and G. Strbac, 1998. Application of STATCOMs to wind Farms. IEE P. Gener. Transm. D., 145(5): 511-516.

Schauder, C. and A.H. Mehta, 1993. Vector Analysis and Control of Advanced Static VAR Compensator. In the Proceedings of the IEE Conference, pp: 299-306.

Schauder, C., M. Gernhardt, E. Stacey, T.W. Cease and A. Edrise, 1995. Development of a ±100 MVAR static condenser for voltage control of transmission systems. IEEE T. Power Deliver., 10(3): 1486-1496.

Sul, S.K., 2011. Control of Electric Machine Drive Systems. John Wiley & Sons, Inc., Hoboken, New Jersey.

Tambey, N. and M.L. Kothari, 2003. Damping of power system oscillation with unified power flow controller (UPFC.) IEE P. Gener. Transm. D., 150(2): 129-140.

Trainner, D.R., S.B. Tennakoon and R.E. Morrison, 1994. Analysis of GTO-based static var compensators. IEE P. Gener. Transm. D., 141(6): 293-302.

Wang, H.F., 1999. Phillips-Heffron model of power systems installed with STATCOM and applications. IEE P. Gener. Transm. D., 146(5): 521-527.