Parameter Optimization of Shunt FACTS Controllers for Power System Transient Stability Improvement

Ahsanul Alam, and M. A. Abido, *Member, IEEE*

Abstract— **To enhance power system transient stability, shunt FACTS devices can be controlled in discontinuous mode or in a combination of discontinuous and continuous mode. In continuous mode proportional controller is usually used. This paper investigates the performance of others controllers in continuous mode. Two additional controllers – PI and lead-lag, have been considered. Controller parameter values have been optimized for minimum settling time. This study shows that both PI and lead-lag controllers have good potential for improving critical clearing time. It also shows that properly selected controller parameter values can reduce settling time significantly. The obtained results are verified using non-linear time-domain simulation for both single-machine infinite-bus (SMIB) and multi-machine (10 machine 39 bus) case.**

Index Terms— **Transient stability, shunt FACTS devises, bang-bang control, continuous and discontinuous mode control, critical clearing time.**

I. INTRODUCTION

Maintenance of stability is an essential prerequisite for reliable and efficient operation of power systems. With the introduction of FACTS devices in the late 80's there opened a new horizon for damping of power system oscillation. Although the main objectives of FACTS are to increase the usable transmission capacity of lines, provide voltage support and control the power flow over designed routes, a number of studies have demonstrated that properly controlled FACTS devices can make significant improvement in the transient as well as dynamic performance of the power system [1]-[8]. Speed based bang-bang control (BBC) i.e. discontinuous control is usually used for shunt FACTS devices to improve the transient stability and damping of power system [3], [9]. Because this type of control strategy helps maximize the

decelerating area required for counterbalancing the accelerating area following large disturbance. Recently it is realized that bang-bang control possess some drawbacks and cannot utilize entire decelerating area in counterbalancing the accelerating area [10]. Therefore it provides lesser stability limit. More recently M. H. Haque [10] demonstrated that with a combination of discontinuous and continuous control strategy transient stability limit can be substantially improved.

In continuous mode proportional controller is usually used [10, 11] as the damping torque provided by the controller is directly proportional to controller gain. In [12] it is suggested that by selecting proper value of controller gain, settling time and overshoot of subsequent peaks can be reduced, and thereby controller performance can be improved. For the power system dynamic stability, a wide variety of approaches have been proposed for tuning power system stabilizer (PSS) parameters. This includes – pole placement, damping torque concept, variable structure, and different optimization and artificial intelligence techniques. Recently the use of heuristic techniques for PSS tuning have showed promising results and confirmed the potential of these algorithms for optimal PSS design [13]-[16]. This motivates us to use Particle Swarm Optimization (PSO) technique optimize the controller gain for minimum settling time and overshoot.

This paper investigates the performance of others controllers in continuous mode. Two additional controllers – PI and lead-lag, have been considered. Controller parameter values have been optimized for minimum settling time. This study shows that both PI and lead-lag controllers have good potential for improving critical clearing time. It also shows that properly selected controller parameter values can reduce settling time significantly. The obtained results are verified using non-linear time-domain simulation for both single-machine infinite-bus (SMIB) and multi-machine (10 machine 39 bus) case.

II. ENHANCEMENT OF TRANSIENT STABILITY BY SHUNT FACTS DEVICES

Equal-area criterion is commonly used for the assessment of transient stability of power system where power system representation is usually simplified as single machine infinite

Ahsanul Alam is with the Electrical Engineering Department, Dhaka University of Engineering & Technology, Gazipur – 1700, Bangladesh. Presently he is at KFUPM, KSA. e-mail: mahsanul@ kfupm.edu.sa).

M. A. Abido is with the Electrical Engineering Department, King Fahd University of Petroleum and Minerals, Dhahran – 31261, Saudi Arabia (corresponding author : 966-03-8604379; fax: 966-03-8603535; e-mail: mabido@ kfupm.edu.sa).

bus (SMIB) system [13]. For the sake of analysis, let us consider a lossless SMIB system with a shunt FACTS device as shown in Fig. 1(a) and (b), where E' and V represent the machine internal voltage and infinite bus voltage. The dynamics of the machine, in classical model, can be represented by the following differential equations [17]
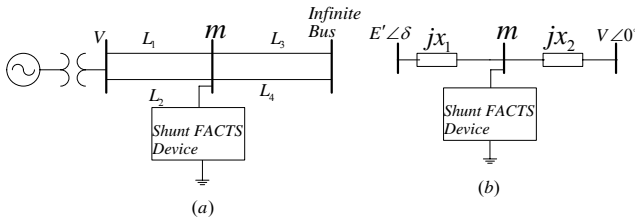

Fig. 1. A SMIB with a shunt FACTS device: (a) single line diagram and (b) equivalent circuit.

$$\frac{d\delta}{dt} = \omega \tag{1}$$

$$\frac{d\omega}{dt} = \frac{1}{M}(P_m - P_e - D\omega) \tag{2}$$

Here, δ, ω, M, D, P_m and P_e are angle, speed, moment of inertia, damping coefficient, input mechanical power and output electrical power, respectively, of the machine. The electrical output power without FACTS devices P_{e0} of the machine can be written as

$$P_{e0} = \frac{E'V}{(X_1 + X_2)}\sin\delta \ \square \ P_{max}\sin\delta \tag{3}$$
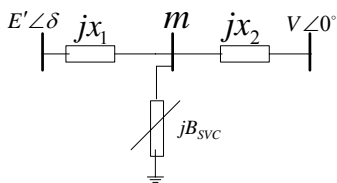
A. System with a SVC

Fig. 2. A SMIB system with a SVC.

A SVC can be modeled by a variable shunt susceptance B_{SVC} as shown in Fig. 2 [2]. For a given B_{SVC}, the transfer reactance X_{12} between machine internal bus and the infinite bus can written as

$$X_{12} = X_1 + X_2 - B_{SVC}X_1X_2 \tag{4}$$

The electrical power output P_e of the machine is

$$P_e = \frac{E'V}{X_{12}}\sin\delta \tag{5}$$

So with proper control of B_{SVC}, P_e of the machine can be controlled to improve the dynamic performance of the system.

B. System with a STATCOM

A STATCOM is a voltage-source converter (VSC) based shunt FACTS device [1]. It is capable of injecting controllable reactive power into the system. Fig.4 (a) shows a SMIB system with a STATCOM is placed at bus m and its equivalent circuit is shown in Fig. 3(b) where the STATCOM is represented by a shunt reactive current source $\mathbf{I_S}$ [1], [2]. When the STATCOM operates in capacitive mode, $\mathbf{I_S}$ can be expressed as

$$\mathbf{I_S} = I_S e^{j(\delta_m - \pi/2)} \tag{6}$$

here δ_m is the angle of voltage at bus m and is given by

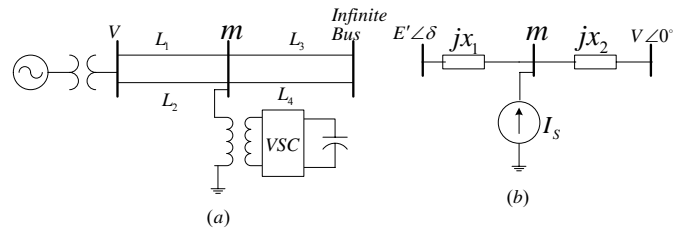$$\delta_m = \tan^{-1}\left(\frac{E'X_2 Sin\delta}{VX_1 + E'X_2 Cos\delta}\right) \tag{7}$$

Fig.3. A SMIB system with a STATCOM. (a) single line diagram and (b) equivalent circuit.

For inductive mode of operation, I_S in (6) is to be replaced by $-I_S$. The electric power output of the machine P_{e1} can be written as [19]

$$P_{e1} = P_{e0} + \frac{E'X_2}{X_1 + X_2}I_S Sin(\delta - \delta_m) \tag{8}$$

Thus the dynamic equation of the system with STATCOM becomes

$$\frac{d\delta}{dt} = \omega \tag{9}$$

$$\frac{d\omega}{dt} = \frac{1}{M}[P_m - P_{e0} - \frac{E'X_2}{X_1 + X_2}I_S Sin(\delta - \delta_m) - D\omega] \tag{10}$$

From (8) we see that Pe0 can be modulated by STATCOM.

III. CONTROL STRATEGY

Shunt FACTS devices can be operated either in capacitive mode or in inductive mode. With the occurrence of a large disturbance, the first objective of the controller is to maximize the first swing stability limit by enlarging the decelerating area as much as possible and fully utilizing it in counterbalancing the accelerating area. This calls for the bang-bang control (BBC) strategy as suggested [3], [11]. This will drive the FACTS devices to operate at its full capacitive rating in early part of the post fault period until the speed becomes negative. But lately it is commented that bang-bang control strategy cannot utilize entire decelerating area in counterbalancing the accelerating area [10]. Also it causes the machine to operate around the equilibrium point (stable or unstable) for a long time (see Fig. 5(a) & (b)). In [10] a new control strategy is proposed which operates the FACTS device at its full capacitive rating in the early part of the post-fault period until the machine speed reaches a reasonable negative value during the first return journey. Afterwards, a linear continuous control is applied to improve damping in subsequent swings. The detail of such a control strategy is can be found in [10] and is given in the following.

For the SVC:

$$B_{SVC} = \begin{cases} 0; \ for \ t \le t_{cl} \\ B_{SVC}^{\max}; \ for \ t \ge t_{cl} \ \& \ \omega > -\gamma\omega_m \ (first\ swing) \\ f(\omega); \ B_{SVC}^{\min} \le f(\omega) \le B_{SVC}^{\max} \ (afterwards) \end{cases} \quad (11)$$

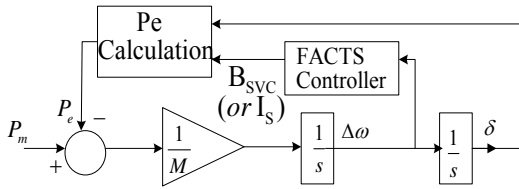Fig.4. Simulation block diagram

For the STATCOM:

$$I_S = \begin{cases} 0; \ for \ t \le t_{cl} \\ I_S^{\max}; \ for \ t \ge t_{cl} \ \& \ \omega > -\gamma\omega_m \ (first\ swing) \\ f(\omega); \ I_S^{\min} \le f(\omega) \le I_S^{\max} \ (afterwards) \end{cases} \quad (12)$$

Here t_{cl} is the fault clearing time, ω_m is the maximum machine speed and γ is small positive constant.

Fig. 6 shows the comparison of critical clearing times (CCTs) obtained from two different control strategies. Top two curves are for *discontinuous then continuous* (let it be called BBC+) and the bottom one is for BBC. Clearly it shows that BBC+ always gives higher value of CCTs with same FACTS device rating.
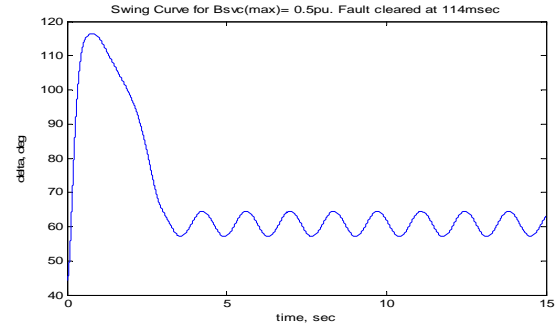
(a)
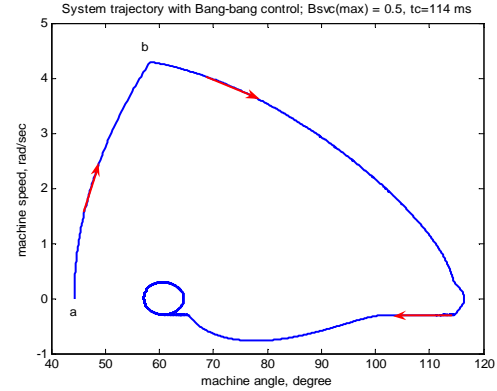
(b)

Fig. 5. Typical response of SMIB system with bang-bang control (a) Swing curve (b) System trajectory
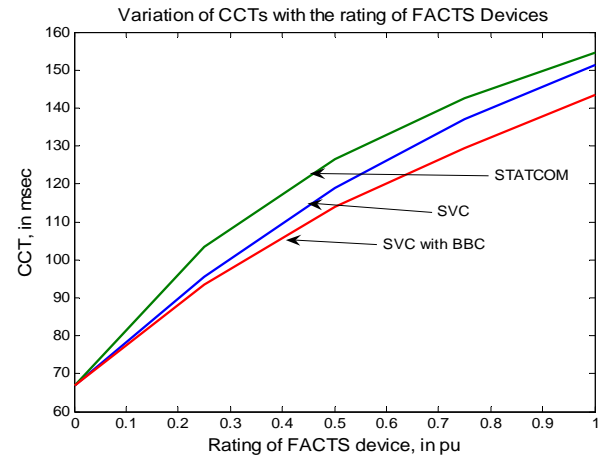
Fig. 6. Comparison of CCTs obtained from two different control strategies.

IV. OPTIMIZATION OF CONTROLLER PARAMETERS

In continuous mode, the response of three types of controller viz. proportional, proportional plus integral (PI), and lead-lag, were investigated. The structures of the controllers are shown in Fig. 7.

To optimize the controller parameters (K's and T's) those most enhances the power system transient performance, the following objective function was used

$$J = \int_{t=0}^{t=t_{sim}} (t\Delta\omega)^2 \, dt \qquad (13)$$

where $\Delta\omega$ is the deviation in machine speed, t_{sim} is the simulation time. The term J in (13) reflects the settling time of the controller. The optimization problem is formulated as

min J

Subjected to

$$K_p^{min} \leq K_p \leq K_p^{max} \qquad (14)$$

$$K_i^{min} \leq K_i \leq K_p^{max}$$

$$T_1^{min} \leq T_1 \leq T_1^{max}$$

Particle Swarm Optimization (PSO) technique [20, 21] is used to the above optimization problem to search for the optimum value of the controller parameters. An excellent simplified description of PSO algorithm can be referred to in [16]. A similar procedure to that presented in [16] is employed here. Obtained optimum values of K's and T_1's for the two shunt FACTS devices (SVC and STATCOM) are tabulated in Table I and Table II. It is observed that the optimum parameter values depend on FACTS device type as well as ratings.
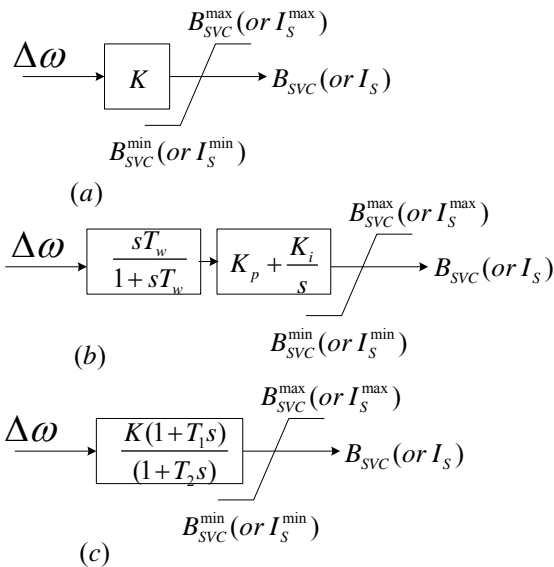

Fig.7. Structure of three types controller considered (a) proportional (b) proportional plus integral (PI) (c) lead-lag

V. CONTROLLER PERFORMANCE

To evaluate controller performance, settling time and CCTs with each controller are determined and compared.

A. Settling Time T_s

With same set of system and disturbance conditions, performance index (J) reflecting settling time for each

TABLE I
OPTIMUM PARAMETER VALUES FOR CONTROLLER WITH SVC

Device ratings	For controller P, PI, and LL respectively		
	K	K_p, K_i	K, T_1 T_2=0.1
0.25	0.75	0.5443, 2.0	1.5, 0.0637
0.50	0.75	0.489, 2.0	2.5, 0.1173
0.75	0.50	0.7724, 2.0	1.5, 0.15
1.00	0.40	0.7918, 2.0	1.929, 0.1617

TABLE II
OPTIMUM PARAMETER VALUES FOR CONTROLLER WITH STATCOM

Device ratings	For controller P, PI, and LL respectively		
	K	K_p, K_i	K, T_1 T_2=0.1
0.25	0.4	0.5541, 2.0	0.4584, 0.12
0.50	0.35	0.65, 0.75	0.4, 0.12
0.75	0.35	0.65, 0.95	0.4, 0.15
1.00	0.30	0.65, 1.0	0.1775, 0.1121

TABLE III
COMPARISON OF PERFORMANCE INDEX
(STATCOM , I_s(max) = 0.5 pu, t_{cl} = 127 msec)

Controllers	Controller parameters	Performance index, PI ($\times 10^4$)
Proportional	K = 0.2	1.3084
Proportional (optimized)	Kopt = 0.35	1.0001
PI	Kp = 0.65, Ki = 0.75	0.6555
Lead-lag (T_2=0.1)	K = 0.4, T_1 = 0.75,	0.62042

TABLE IV
CCTs (in msec) WITH DIFFERENT TYPES OF CONTROLLERS

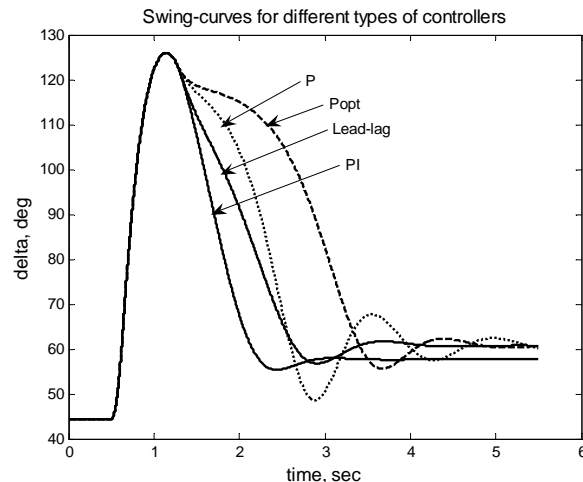| Device Rating (STATCOM)	Types of controllers		
	Proportional	PI	Lead-lag
0.25	104	104	104
0.50	127	129	129
0.75	143	150	145
1.00	156	168	165

Fig. 8. Angle response from different types of controller with system condition mentioned in Table I.

controller is determined and compared. From Table III it is clear that performance index of PI and lead-lag controller is much better than that of P controller. Fig.8 shows the angle response from each controller for the condition mentioned above. In most cases it is found that with the optimum parameter values the machine swing settles at less than 4 sec, where as with P controller it is more than 7 sec.
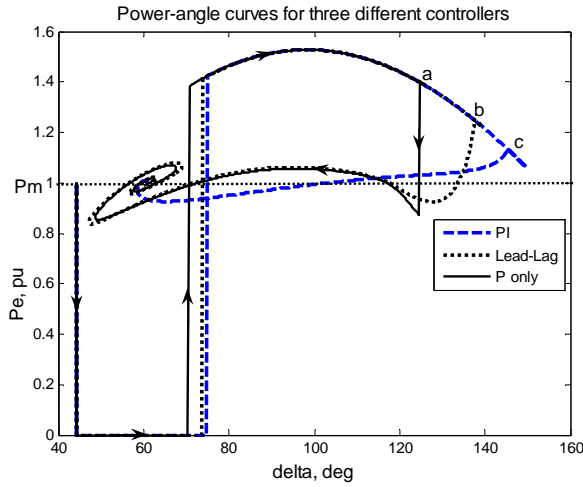

Fig. 9. Power-angle curve with three different types of controller. I_s (max) = 1.0 pu and corresponding CCTs with P, PI and lead-lag controllers as mentioned in Table IV.
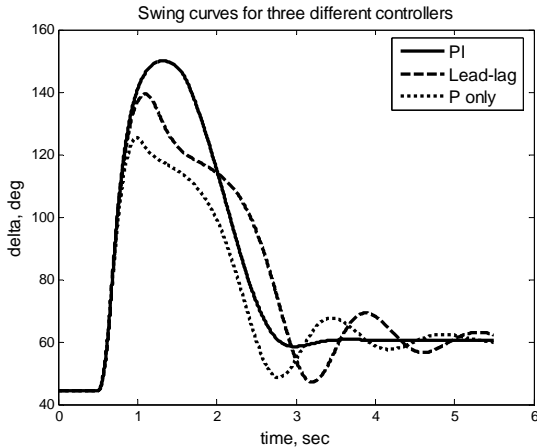

Fig. 10. Angle response with three controllers for condition mentioned in Fig. 9.

B. Critical clearing time (CCT)

Of particular interest it is observed that with PI or lead-lag controller much higher critical clearing time (CCT) can be obtained than that of P controller as shown in Table IV. This could be attributed to the controller dynamics involved. Fig. 9 shows the power-angle curves for the critical clearing conditions with different controllers. With P controller, it switches to continuous mode at point 'a' whereas lead-lag controller switches a bit later at point 'b', and PI controller switches even much more later at point 'c'. The dynamics
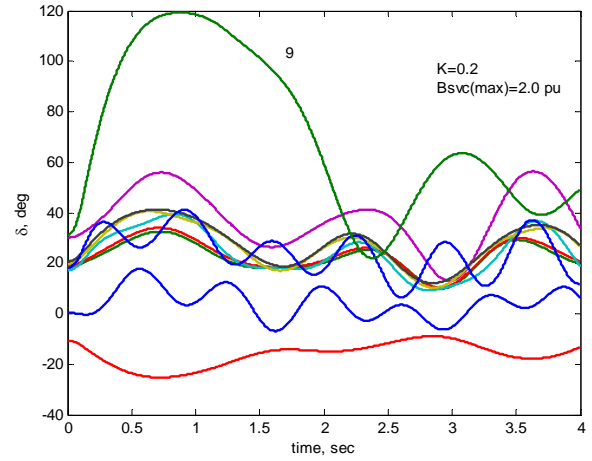
(a)
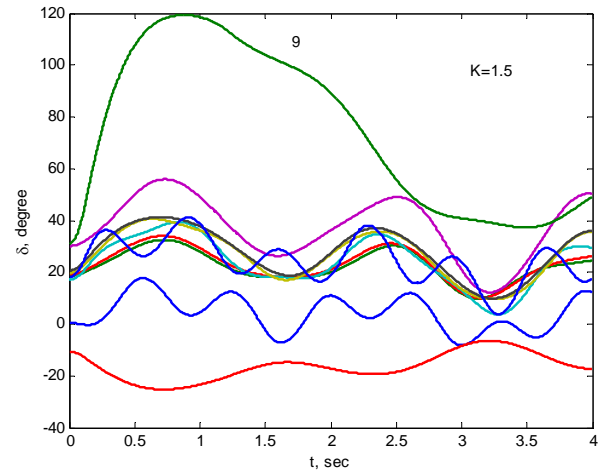
(b)

Fig. 11: Angle response with10 machine 39 bus New England system (a) with arbitrary gain value (b) with optimized gain value.

involved in the lead-lag or PI controller prevents sharp changes of STATCOM's I_s and the resulting P_e, after switching to continuous mode. This allows to have higher decelerating area A_d required for counter balancing greater accelerating area A_c associated with larger CCTs. Fig. 10 shows the swing-curves for the critical clearing conditions with different controllers.

C. Simulation with multi-machine system

Simulations for multi-machine system were carried out with 10 machine, 39 bus New England system considering 3-phase fault at different locations. Fig. 11 shows one of those results where as a transient disturbance, a 3-phase fault on bus 26 is considered which was cleared by opening the lines between 26 and 29. With this condition machine 9 was identified as severely disturbed machine. The critical clearing time is 126

ms. Swing curves for two different values of K=0.2 (arbitrarily chosen) and K=1.5 (optimum value) were generated and are shown in Fig. 11 (a) and Fig. 11 (b) respectively. It is clear that Fig. 11 (b) shows much better angle response. Full development of simulation results with PI and lead-lag controller still under process and will appear in the future publication.

VI. CONCLUSION

Performance of three different controllers for shunt FACTS devices (SVC and STATCOM) for the improvement of transient stability is investigated. Proportional, proportional plus integral, and lead-lag controllers have been considered. Controller parameter values have been optimized for minimum settling time. This study shows that both PI and lead-lag controllers have good potential for improving critical clearing time. It also shows that properly selected controller parameter values can reduce settling time significantly. The obtained results are verified using non-linear time-domain simulation for both single-machine infinite-bus (SMIB) and multi-machine (10 machine 39 bus) case.

APPENDIX

Data of the SMIB system:
Generator: H= 5 sec, f= 60 Hz, X′=0.3 pu,
Transformer: X=0.1 pu; Transmission line: X=0.4 pu of each line
The machine delivers a power of 1.0 pu at the terminal voltage of 1.0 pu and infinite bus voltage V= 0.95 pu.
A tree-phase fault on line 3 near bus is considered, and the fault is cleared by opening the line at both end.

ACKNOWLEDGEMENTS

REFERENCES

[1] N. G. Hingorani, and L. Gyugyi: 'Understanding FACTS: Concepts and technology of flexible AC transmission systems' (IEEE Press, New York, 1999).

[2] Y. H. Song, and A. T. Johns: 'Flexible AC transmission systems (FACTS)' (IEE Power and Energy Series 30, London, UK, 1999).

[3] E. Z, Zhou.: 'Application of static var compensators to increase power system damping', IEEE Trans. Power System, vol.8, pp. 655-661, 1993.

[4] M.A. Abido, "Analysis and assessment of STATCOM-based damping stabilizers for power system stability enhancement", *Electric Power Systems Research, vol 73, Issue 2, 2005, pp. 177-185.*

[5] M. A. Abido and Y. L. Abdel-Magid, "Coordinated design of a PSS and an SVC-based controller to enhance power system stability", *Int. J. of Electrical Power & Energy Systems, vol. 25, Issue 9, 2003, Pages 695-704.*

[6] M.A. Abido;, "Design of PSS and STATCOM-based damping stabilizers using genetic algorithms", IEEE PES General Meeting, 2006. 18-22 June 2006 Page(s): 8 pp.

[7] M.A. Abido; Al-Awami, A.T.; Abdel-Magid, Y.L.; "Simultaneous design of damping controllers and internal controllers of a unified power flow controller", IEEE PES General Meeting, 2006. 18-22 June 2006 Page(s):8 pp.

[8] T. Kondo et al: 'Power System Transient Stability enhancement by STATCOM with nonlinear control system', IEEE Conf. pp. 1908-1912, 2002.

[9] D. N. Kosterev, W. J. Kolodziej, "Bang-bang series capacitor transient stability control", IEEE Trans. Power System, vol. 10, no. 2, pp. 915-924, 1995.

[10] M. H. Haque: 'Improvement of First swing stability limit by utilizing full benefit of shunt FACTS devices', IEEE Trans. on Power Systems, vol. 19, No. 4, pp. 1894-1902. 2004.

[11] A. E. Hammad: 'Analysis of power system stability enhancement by Static Var Compensator', IEEE Trans on Power System, vol, 1, No.4, 1986.

[12] Ahsanul Alam, M. A. Abido, "On the control strategies of shunt FACTS devices for the improvement of transient stability", in Proc. 2nd Int. Conf. on Modeling, Simulation, and Applied optimization, PI, Abu Dhabi, March 25-27, 2007.

[13] M. A. Abido, "Pole placement technique for PSS and TCSC-based stabilizer design using simulated annealing", *Int. J. Electrical Power & Energy Systems, vol. 22, Issue 8, 2000, Pages 543-554.*

[14] M. A. Abido "Simulated annealing based approach to PSS and FACTS based stabilizer tuning", *Int. J. of Electrical Power & Energy Systems, vol 22, Issue 4, May 2000, Pages 247-258.*

[15] Y. L. Abdel-Magid and M. A. Abido, "Robust coordinated design of excitation and TCSC-based stabilizers using genetic algorithms", *Electric Power Systems Research, Volume 69, Issues 2-3, May 2004, Pages 129-141.*

[16] M. A. Abido, "Optimal design of power system stabilizers using Particle Swarm Optimization", IEEE Trans. Energy Conversion, vol. 17, no. 3, 2002. pp. 406-413.

[17] P. M. Anderson, and A. A. Fouad, "Power system control and stability", vol. I, Ames, IA: Iowa State Univ. Press, 1997.

[18] M. H. Haque, and P. Kumkratung, : 'Application of Lyapunov stability criterion to determine the control strategy of a STATCOM', IEE Proc. Generation, Transmission, Distribution, 151, (3), pp. 415-420. 2004.

[19] P. Kumkratug, and M.H. Haque: 'Versatile model of a unified power flow controller in a simple power system', IEE Proc. Generation, Transmission, Distribution, 150, (2), pp. 155-161. 2003.

[20] J. Kennedy, "The particle swarms: Social adaptation of knowledge", in *Proc. IEEE Int. Conf. Evolutionary Comput., Indianapolis, IN, 1997*, pp. 303-308, 1997.

[21] M. Clerc, and J. Kennedy, "The Particle Swarm – Explosion, stability, and convergence in a multidimensional complex space", *IEEE Trans. On Evolutionary computation*, vol. 6, no. 1, pp. 58-73, Feb. 2002.