

Dynamic stability enhancement of power system using STATCOM

Shoorangiz Shams Shamsabad Farahani*, Mehdi Nikzad, Mohammad Bigdeli Tabar,
Behrang Yousefpour and Hossein Tourang

Department of Electrical Engineering, Islamshahr Branch, Islamic Azad University, Tehran, Iran
shoorangiz.farahani@yahoo.com*; mehdi.nikzad@yahoo.com; bigdeli@iiu.ac.ir;
behrang1358@yahoo.com; h_tourang@yahoo.com

Abstract

In this paper multi-objective tuning of a supplementary stabilizer for Static Synchronous Compensator (STATCOM) is presented. A meta-heuristic optimization method named genetic algorithms (GA) is used for tuning the parameters of the proposed stabilizer. The potential of the GA for optimal setting of the proposed stabilizer are investigated. The stabilizer is designed to shift slightly damped and undamped electromechanical modes of power system. The validity of the proposed method is verified on a single-machine infinite-bus power system (SMIB) installed with a STATCOM. Several linear time-domain simulation tests visibly show the validity of proposed method in damping of power system oscillations.

Keywords: Flexible AC Transmission Systems, Static Synchronous Compensator, Low Frequency Oscillations, Genetic Algorithms, Power System Stabilizer.

Abbreviations

FACTS: Flexible AC Transmission Systems; GA: Genetic Algorithms; LFO: Low Frequency Oscillations; SIMB: Single-Machine Infinite-Bus Power System; STATCOM: Static Synchronous Compensator

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 are 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; Mehrdad Ahmadi Kamarposhti, 2010; Mehdi Nikzad *et al.*, 2011; Reza Hemmati *et al.*, 2011; Sayed Mojtaba Shirvani Boroujeni *et al.*, 2011; Hasan Fayazi Boroujeni *et al.*, 2011). 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, 1979; Gyugyi *et al.*, 1990; Schauder *et al.*, 1993; Mori *et al.*, 1993; Trainner *et al.*, 1994; Schauder *et al.*, 1995; Ekanayake *et al.*, 1995; Saad-Saoud *et al.*, 1998; Ainsworth *et al.*, 1998; Reza Hemmati *et al.*, 2011; Sayed Mojtaba Shirvani Boroujeni *et al.*, 2011).

Wang *et al.* (1999) studied a unified Phillips-Heffron model (Heffron *et al.*, 1952) of power systems installed with a STATCOM. STATCOM has developed from a switch mode voltage-source converter configuration with

an energy-storage device (DC capacitor). Also, the STATCOM can be used for voltage support and transient stability improvement by damping of low frequency power system oscillations. 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. In past decays power system stabilizer or PSS was applied for damping power system oscillations. Recently new power system controllers like as FACTS devices are presented as power system stabilizer. Many in the past have presented lead-Lag type UPFC stabilizers (Tambey *et al.*, 2003). They are designed for a specific operating condition using linearized models. More advanced control schemes such as self-tuning control (Cheng *et al.*, 1986), Particle-Swarm method (Al-Awami *et al.*, 2007) and fuzzy logic control (Mishra *et al.*, 2000; Eldamaty *et al.*, 2005) offer better dynamic performances than fixed parameter controllers. Fuzzy control design is attractive because it does not require a mathematical model of the system under study and it can cover a wide range of operating conditions and is simple to implement.

The objective of this paper is to investigate the ability of Genetic algorithms (GA) for STATCOM supplementary stabilizer design. A Single Machine Infinite Bus (SMIB) power system installed with a STATCOM is considered as case study and a STATCOM based stabilizer whose parameters are tuned using GA is considered as power system stabilizer. Different load conditions are considered to show effectiveness of the proposed method. Simulation results show the validity of proposed method in LFO damping.

Illustrative test

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

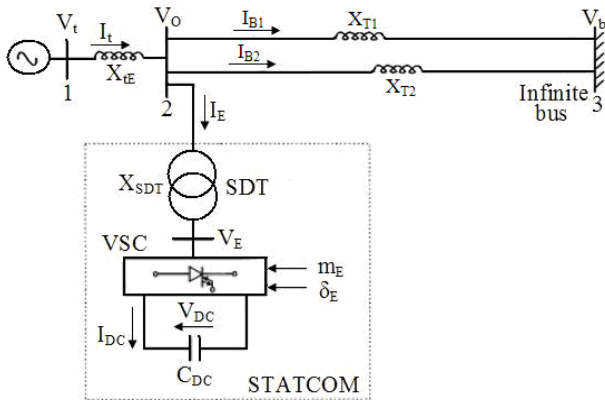


Fig.1 shows the case study system in this paper. The system is a Single Machine Infinite Bus (SMIB) power system with STATCOM installed. The system parameters are presented in appendix.

System modeling

Nonlinear model

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 below (1) (Wang *et al.*, 1999).

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

Linear model

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

$$\begin{cases}
 \Delta \dot{\delta} = \omega_0 \Delta \omega \\
 \Delta \dot{\omega} = (-\Delta P_e - D\Delta \omega)/M \\
 \Delta \dot{E}'_q = (-\Delta E_q + \Delta E_{fd})/T'_{do} \\
 \Delta \dot{E}_{fd} = -(1/T_A)\Delta E_{fd} - (K_A/T_A)\Delta V_t \\
 \Delta \dot{V}_{dc} = K_7 \Delta \delta + K_8 \Delta E'_q - K_9 \Delta V_{dc} + K_{ce} \Delta m_E + K_{c\delta e} \Delta \delta_E
 \end{cases} \quad (2)$$

Where

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

Fig.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).

$$U = [\Delta m_E \quad \Delta \delta_E]^T \quad (3)$$

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.

$\Delta \delta_E$: 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:

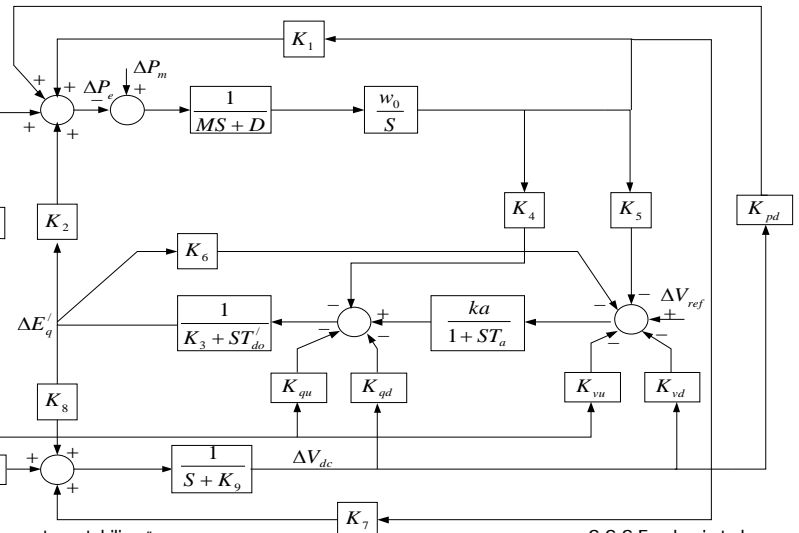
$$\begin{aligned}
 K_{pu} &= [K_{pe} \quad K_{p\delta e}]; K_{qu} = [K_{qe} \quad K_{q\delta e}]; \\
 K_{vu} &= [K_{ve} \quad K_{v\delta e}]; K_{cu} = [K_{ce} \quad K_{c\delta e}]
 \end{aligned}$$

State space model

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

$$\begin{bmatrix} \Delta \dot{\delta} \\ \Delta \dot{\omega} \\ \Delta \dot{E}'_q \\ \Delta \dot{E}_{fd} \\ \Delta \dot{V}_{dc} \end{bmatrix} = \begin{bmatrix} 0 & \omega_0 & 0 & 0 & 0 \\ -\frac{K_1}{M} & 0 & -\frac{K_2}{M} & 0 & -\frac{K_{pd}}{M} \\ -\frac{K_4}{T'_{do}} & 0 & -\frac{K_3}{T'_{do}} & \frac{1}{T'_{do}} & -\frac{K_{qd}}{T'_{do}} \\ -\frac{K_A K_5}{T_A} & 0 & -\frac{K_A K_6}{T_A} & -\frac{1}{T_A} & -\frac{K_A K_{vd}}{T_A} \\ K_7 & 0 & K_8 & 0 & -K_9 \end{bmatrix} \times \begin{bmatrix} \Delta \delta \\ \Delta \omega \\ \Delta E'_q \\ \Delta E_{fd} \\ \Delta V_{dc} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ -\frac{K_{pe}}{M} & -\frac{K_{p\delta e}}{M} \\ -\frac{K_{qe}}{T'_{do}} & -\frac{K_{q\delta e}}{T'_{do}} \\ -\frac{K_A K_{ve}}{T_A} & -\frac{K_A K_{v\delta e}}{T_A} \\ K_{ce} & K_{c\delta e} \end{bmatrix} \times \begin{bmatrix} \Delta m_E \\ \Delta \delta_E \end{bmatrix} \quad (4)$$

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





STATCOM Controllers

The STATCOM control system comprises two controllers:

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

DC-voltage regulator

The STATCOM needs to a DC voltage regulator to regulate DC-link voltage. DC-voltage is regulated by modulating the phase angle of the shunt converter voltage. A PI type controller is considered as voltage regulator here. The parameters of DC-voltage regulator are considered as follow for this research: $K_{df}=39.8$ and $K_{dp}=0.5778$.

Supplementary stabilizer

As referred before, in large interconnected power systems, the damping torque of overall system is neglect and system need to stabilizer for stability. The basic function of stabilizer is to add damping torque to the generator rotor oscillations by controlling its excitation using auxiliary stabilizing signal. To provide damping, the stabilizer must produce a component of electrical torque in phase with the rotor speed deviations. The stabilizer configuration is given in (5). Where, $\Delta\omega$ is the speed deviation in per unit. This type of stabilizer consists of a washout filter and a dynamic compensator. The output signal is fed as a supplementary input signal to the input of STATCOM. The washout filter, which is a high pass filter, is used to reset the steady state offset in the stabilizer output. In this paper the value of the time constant (T_w) is fixed to 10 s. The dynamic compensator is made up to two lead-lag stages with time constants, $T1-T4$ and an additional gain K_{DC} .

$$U = K_{DC} \frac{ST_w}{1+ST_w} \frac{1+ST_1}{1+ST_2} \frac{1+ST_3}{1+ST_4} \Delta\omega \quad (5)$$

The major point in the stabilizer design is to find the values of K_{DC} and $T1-T4$. In this paper GA method is used to find the values of the proposed parameters. Where, the robust values of K_{DC} and the time constants of $T1-T4$ are obtained by using GA.

Eigen value analysis

For the nominal operating condition the eigenvalues of the system are obtained using state-space model of the system presented in (4) 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). But PSS cannot control power transmission and also cannot support power system stability under large disturbances like 3-phase fault at terminals of generator. For these problems, in this paper a stabilizer controller based STATCOM is provided to mitigate power system oscillations. An optimization

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

-17.1146
+0.0213±3.7111i
-0.5401±0.4991i

method named GA is considered for tuning stabilizer controller parameters (Shoorangiz Shams Shamsabad Farahani *et al.*, 2011a,b).

Genetic algorithms

Genetic algorithms (GA) are global search techniques, based on the operations observed in natural selection and genetics. They operate on a population of current approximations-the individuals-initially drawn at random, from which improvement is sought. Individuals are encoded as strings (chromosomes) constructed over some particular alphabet, e.g., the binary alphabet {0,1}, so that chromosomes values are uniquely mapped onto the decision variable domain. Once the decision variable domain representation of the current population is calculated, individual performance is assumed according to the objective function which characterizes the problem to be solved. It is also possible to use the variable parameters directly to represent the chromosomes in the GA solution. At the reproduction stage, a fitness value is derived from the raw individual performance measure given by the objective function and used to bias the selection process. Highly fit individuals will have increasing opportunities to pass on genetically important material to successive generations. In this way, the genetic algorithms search from many points in the search space at once and yet continually narrow the focus of the search to the areas of the observed best performance. The selected individuals are then modified through the application of genetic operators. In order to obtain the next generation Genetic operators manipulate the characters (genes) that constitute the chromosomes directly, following the assumption that certain genes code, on average, for fitter individuals than other genes. Genetic operators can be divided into three main categories: Reproduction, crossover and mutation (Randy & Sue, 2004).

Design methodology

In this section the parameters of the proposed stabilizer are tuned using GA. Two control parameters of the STATCOM (m_E and δ_E) can be modulated in order to produce the damping torque. The parameter m_E is modulated to output of stabilizer and speed deviation $\Delta\omega$ is also considered as input of stabilizer. The optimum values of K_{DC} and $T_1 - T_4$ which minimize an array of different performance indexes are accurately computed using GA. In optimization methods, the first step is to define a performance index for optimal search. The objective function (performance index) is presented in the next subsection.

Performance index

In electric power systems, the unstable poles or lightly damped stable poles cause the great oscillations and instability. Therefore, in this paper only the unstable or lightly damped electromechanical modes of oscillations are relocated. In this scope, an eigenvalue based multi-objective function reflecting the combination of damping

factor and damping ratio is considered as follows (Shayeghi *et al.*, 2010):

$$J_3 = J_1 + aJ_2 \tag{6}$$

Where,

$$J_1 = \sum_{j=1}^{NP} \sum_{\sigma_i > \sigma_0} (\sigma_0 - \sigma_{ij})^2 \text{ and } J_2 = \sum_{j=1}^{NP} \sum_{\xi_i \geq \xi_0} (\xi_0 - \xi_{ij})^2$$

The parameters σ_{ij} and ξ_{ij} are the real part and the damping ratio of the i_{th} eigenvalue of the j_{th} operating condition. The parameter "a" is a weighting factor and is used to offset the weight of J_1 and J_2 . Since J_2 is almost ten times less than J_1 , therefore, the value of "a" is chosen as 10. NP is the total number of operating points for which the optimization is carried out. The value of σ_0 determines the relative stability in terms of damping factor margin provided for constraining the placement of eigenvalues during the process of optimization. When J_3 is optimized, the eigenvalues are restricted in the dashed region as shown in Fig. 3.

Fig. 3. Region of eigenvalue location for objective function

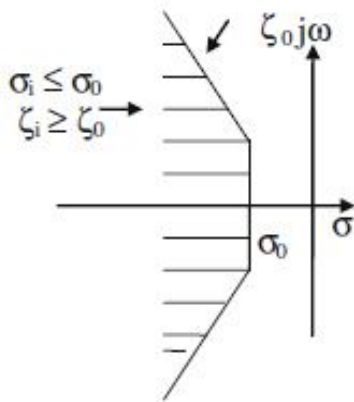


Table 2. Optimum values of stabilizer parameters using GA

K_{DC}	407.55
T_1	0.4761
T_2	0.2105
T_3	0.8133
T_4	0.3501

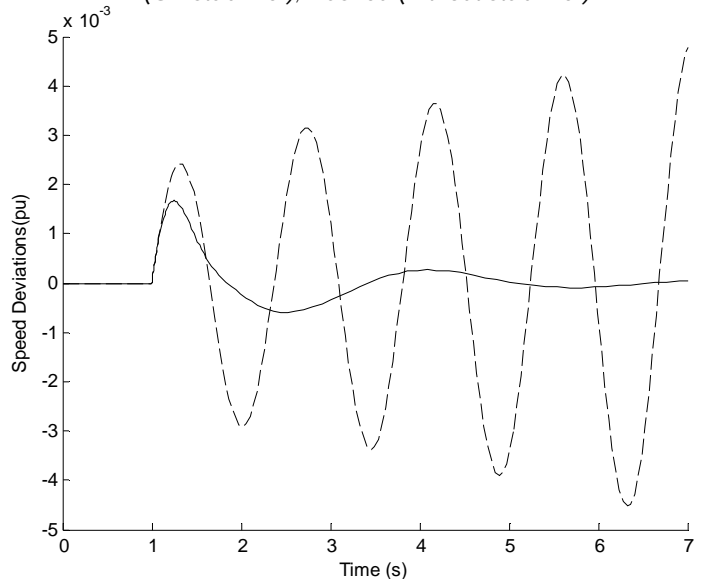
To compute the optimum parameter values, a 0.1 step change in mechanical torque (ΔT_m) is assumed and the performance index is minimized using GA. The optimum values of K_{DC} and T_1 to T_4 , resulting from minimizing the performance index is presented in Table 2. Where, the search area for parameters is considered as $1 < K_{DC} < 1000$ and $0.01 < T < 1$. In GA case, number of chromosomes, population size, crossover rate and mutation rate are set as 5, 48, 0.5 and 0.05.

Simulation results

In this section, the designed GA based stabilizer is applied to system in order to damping low frequency oscillations. 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. GA stabilizer has been designed for the nominal operating condition.

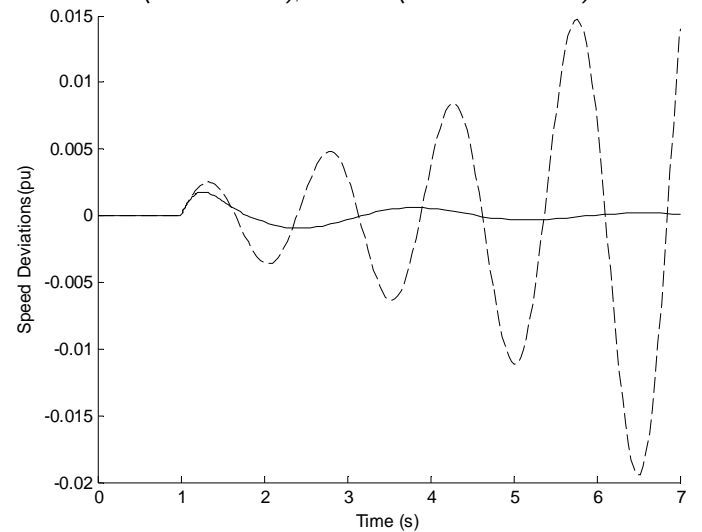
For case 1 the simulation results are shown in Fig. 4. The simulation results show that applying the supplementary control signal greatly enhances the

Fig. 4. Dynamic response $\Delta\omega$ for case 1 Solid (GA stabilizer); Dashed (without stabilizer)



damping of the generator angle oscillations and therefore the system becomes more stable. For case 2, the simulation results are shown in Fig. 5. Under this condition the GA controller has a stable and robust performance. Thus, the GA supplementary controller has suitable parameter adaptation when operating condition changes.

Fig. 5. Dynamic response $\Delta\omega$ for case 2 Solid (GA stabilizer); Dashed (without stabilizer)



Conclusions

In this paper Genetic algorithms has been successfully applied to design stabilizer controller based STATCOM. A Single Machine Infinite Bus power system installed with a STATCOM with various load conditions has been assumed to demonstrate the methods. Simulation results demonstrated that the designed controllers capable of guarantying the robust stability and robust performance

Table 3. System parameters

Generator	M = 8 Mj/MVA X _q = 0.6 p.u.	T _{do} = 5.044 s X'd = 0.3 p.u.	X _d = 1 p.u. D = 0
Excitation system		K _a = 10	T _a = 0.05 s
Transformers		X _{le} = 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.

Table 4. 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 = 1.1 p.u.	Q = 0.35 p.u.	V _t = 1.03 p.u.

under a different load conditions. In addition, GA method has an excellent capability in power system oscillations damping and power system stability enhancement under small disturbances.

Appendix

The nominal parameters and nominal operating condition of the system are listed in Table 3. Also system operating conditions are defined as Table 4 (Operating condition 1 is the nominal operating condition).

Acknowledgement

The authors gratefully acknowledge the financial and other support of this research, provided by Islamic Azad University, Islamshahr Branch, Tehran, Iran.

References

- Ainsworth JD, Davies M, Fitz JB, Owen KE and Trainer DR (1998) Static var compensator (STATCOM) based on single-phase chain circuit converters. *IEE Proc. Generation, Trans. & Distribution*. 145(4), 381-386.
- Al-Awami AT (2007) A particle-swarm-based approach of power system stability enhancement with UPFC. *Electrical Power & Energy Sys.* 29, 251-259.
- Cheng S, Malik OP and Hope SG (1986) Self-tuning stabilizers for a multi-machine power system. *IEE Proc. Part C*. (4), 176-185.
- Ekanayake JB, Jenkins N and Cooper CB (1995) Experimental investigation of an advanced static var compensator. *IEE Proc. Generation, Trans. & Distribution*. 142(2), 202-210.
- Eldamaty AA, Faried SO and S Aboreshaid S (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, Hingorani NG, Nannery PR and Tai T (1990) Advanced static var compensator using gate turn-off thyristors for utility applications. *Proc. 1990 CIGRE Conf.* pp: 23-203.
- Hasan Fayazi Boroujeni, Sayed Mojtaba Shirvani Boroujeni and Reza Hemmati (2011) Robust PID power system stabilizer design based on pole placement and nonlinear programming methods. *Indian J.Sci.Technol.* 4(4),456-461.
- Heffron WG and Phillips RA (1952) Effect of a modern amplydine voltage regulator on under excited operation of large turbine generator. *AIEE Trans.* pp: 71-80.
- Hingorani NG and Gyugyi L (2000) Understanding FACTS. *IEEE Press*. NY.
- Mehdi Nikzad, Shoorangiz Shams Shamsabad Farahani, Mohammad Bigdeli Tabar, Mehdi Ghasemi Naraghi and Ali Javadian (2011) Adjustment of PSS in a multi machine power system based on particle swarm optimization technique. *Indian J.Sci.Technol.* 4 (8), 876-880.
- Mehrdad Ahmadi Kamarposhti (2010) Evaluation of static synchronous compensator in order to loading margin study in power system. *Indian J.Sci.Technol.* 3 (5), 511-514. Domain site: <http://www.indjst.org>.
- Mishra S, Dash PK and Panda G (2000) TS-Fuzzy controller for UPFC in a multi-machine power system. *IEEE Proc. Generation, Transmission & Distribution*. 147(1), 15-22.
- Mori S, Matsuno K, Takeda M and Seto M (1993) Development of a large static var generator using self-commutated inverters for improving power system stability. *IEEE Trans. Power Sys.* 8(1), 371-377.
- Randy LH and Sue EH (2004) Practical genetic algorithms. *John Wiley & Sons*, Second Edition.
- Reza Hemmati, Sayed Mojtaba Shirvani Boroujeni, Elahe Behzadipour and Hamideh Delafkar (2011) Supplementary stabilizer design based on STATCOM. *Indian J.Sci.Technol.* 4 (5), 525-529. Domain site: <http://www.indjst.org>.
- Reza Hemmati, Sayed Mojtaba Shirvani Boroujeni, Hamideh Delafkar and Amin Safarnezhad Boroujeni (2011) Fuzzy load frequency control in multi area electric power system. *Indian J.Sci.Technol.* 4 (7), 796-800.
- Saad-Saoud Z, Lisboa ML, Kanayake JBE, Jenkins N and Strbac G (1998) Application of STATCOMs to wind farms. *IEE Proc. Generation, Trans. & Distribution*. 145(5), 511-516
- Sayed Mojtaba Shirvani Boroujeni, Babak Keyvani Boroujeni, Hamideh Delafkar, Elahe Behzadipour and Reza Hemmati (2011) Harmony search algorithm for STATCOM controllers tuning in a multi machine environment. *Indian J.Sci.Technol.* 4 (9),1031-1035.
- Sayed Mojtaba Shirvani Boroujeni, Reza Hemmati, Hamideh Delafkar and Amin Safarnezhad Boroujeni (2011) Optimal PID power system stabilizer tuning based on particle swarm optimization. *Indian J.Sci.Technol.* 4 (4), 379-383.
- Schauder C and Mehta AH (1993) Vector analysis and control of advanced static VAR compensator. *Proc. IEE Conf.* pp: 299-306.
- Schauder C, Gernhardt M, Stacey E, Cease TW and Edrize A (1995) Development of a ±100 MVAR static condenser for voltage control of transmission systems. *IEEE Trans. on Power Delivery*. 10(3), 1486-1496.
- Shayeghi H, Shayanfar HA, Safari A and Aghmasheh RA (2010) Robust PSSs design using PSO in a multi-machine environment. *Energy Conversion & Mangmt.* 51, 696-702.
- Shoorangiz Shams Shamsabad Farahani, Mehdi Nikzad, Mohammad Bigdeli Tabar, Mehdi Ghasemi Naraghi and Ali Javadian (2011a) Multi-machine power system stabilizer adjustment using genetic algorithms. *Indian J.Sci.Technol.* 4 (8), 881-885. Domain site: <http://www.indjst.org>.
- Shoorangiz Shams Shamsabad Farahani, Mehdi Nikzad, Mohammad Bigdeli Tabar, Mehdi Ghasemi Naraghi and Ali Javadian (2011b) Multi-machine power system stabilizer adjustment using Simulated Annealing. *Indian J.Sci.Technol.* 4 (8), 886-889.
- Tambey N and Kothari ML (2003). Damping of power system oscillation with unified power flow controller (UPFC). *IEE Proc. Generation, Trans. & Distribution*. 150(2), 129-140.
- Trainer DR, Tennakoon SB and Morrison RE (1994) Analysis of GTO-based static VAR compensators. *IEE Proc. Generation, Trans. & Distribution*. 141(6), 293-302.
- Wang HF (1999) Phillips-heffron model of power systems installed with STATCOM and applications. *IEE Proc. Generation, Trans. & Distribution*. 146(5), 521-527.