International Journal of Electrical Engineering.
ISSN 0974-2158 Volume 4, Number 4 (2011), pp. 425-438

http://www.irphouse.com

Voltage Stability Limit Improvement by Reactive Power Flow Control Incorporating TCSC through Particle Swarm Optimization Algorithm

S. Sakthivel[1] and D. Mary[2]

[1]*V.R.S. College of Engineering and Technology, Villupuram, T.N., India*
E-mail:sithansakthi@gmail.com
[2]*Government College of Engineering, Bargur, T.N., India*
E-mail:dmary.1008@yahoo.com

Abstract

Modern power systems are at risks of voltage instability problems due to highly stressed operating condition caused by increased load demand. This paper proposes a Particle Swarm Optimization (PSO) algorithm based optimal reactive power flow control task incorporating only one type of FACTS device. Optimal placement of multi type FACTS devices can naturally manage the reactive power flow control. But for large size power systems, this becomes a tedious work owing to the mathematical complexities and much time for obtaining the optimal results. Optimal location and parameter setting of only one TCSC is considered for an acceptable and suboptimal solution for reactive power flow control and the resultant reactive power reserve. Particle swarm optimization technique optimizes the location and size of TCSC. The effectiveness of the proposed work is tested for IEEE-30 Bus test system.

Keywords: FACTS devices, TCSC, Reactive Power Flow Control, Particle Swarm Optimization Algorithm.

Introduction

The present day power systems are forced to be operated closer to stability limit due to the increase of demand for electric power than ever before. In such a stressed condition, the system may enter into voltage instability problem and it has been found responsible for many system block outs in many countries across the world [1]. A power system needs to be with sufficient reactive reserves to meet the increased reactive power demand under heavily loaded conditions to avoid voltage instability problem.

In a deregulated power system environment, the optimum bidders are chosen based on real power cost characteristics and it results in reactive power shortage and hence the loss of voltage stability of the system. The authors in [2-3] discuss methods to assess voltage stability of power system to find the possible ways to improve the voltage stability limit. The amount of reactive power reserves at the generating stations is a measure of degree of voltage stability. Several papers have been published on reactive power reserve management with the perspective of ensuring voltage stability by ensuring adequate amount of reactive power reserves. In [4], T. Menezes,et.al.propose a strategy to improve the voltage stability by dynamic Var sources scheduling . In [5], the authors introduce a methodology to reschedule the reactive injection from generators and synchronous condensers with the aim of improving the voltage stability margin. This method is formulated based on modal participations factors and an optimal power flow (OPF) wherein the voltage stability margin, as computed from eigenvectors of a reduced Jacobian, is maximized by reactive rescheduling. However, the authors avoid using a security-constrained OPF formulation and thus the computed voltage stability margin from the Jacobian would not truly represent the situation under a stressed condition.

The authors in [6] discuss a hierarchical reactive power optimization scheme which optimizes a set of corrective controls such that the solution satisfies a given voltage stability margin. Bender's decomposition method is employed to handle stressed cases. An alternative approach for optimal reactive power dispatch based on iterative techniques is considered in [7-8]. H. Yoshida,et.al in their work [12]have adopted the easy to implement search algorithm, the Particle Swarm Optimization (PSO) for reactive power and voltage control to improve system stability. Reactive power reserve management rather than reactive power scheduling is proposed in [13] to enhance voltage stability.

The modern power systems are facing increased power flow due to increasing demand and are difficult to control. The rapid development of fast acting and self commutated power electronics converters, well known as FACTS controllers, introduced in 1988 by Hingorani [16] are useful in taking fast control actions to ensure security of power systems. FACTS devices are capable of controlling the voltage angle, voltage magnitude at selected buses and/or line impedance of transmission lines. Thyristor controlled series capacitor (TCSC) is a series connected FACTS device inserted in transmission lines to vary its reactance and thereby reduces the reactive losses and increases the transmission capacity. But the conventional power flow methods are to be modified to take into account the effects of FACTS devices.

Lu et.al [17] presented a procedure to optimally place TCSCs in a power system to improve static security. First the "Single Contingency Sensitivity (SCS)" criterion for a given branch flow is defined. This criterion is then used to develop a branch's prioritizing index in order to rank branches for possible placement of TCSCs. Finally, optimal settings for TCSC parameters are determined for important contingencies. Billinton *et al* [18] presented power system reliability enhancement using a TCSC. Paserba, et.al.[21] consider a thyristor controlled series compensation model for power system stability analysis, to enhance system stability.

The proposed algorithm for reactive power flow control incorporates only one type of FACTS device, the TCSC. The optimal location of TCSCs is done based on different factors such as loss reduction, voltage stability enhancement and reactive power generation reduction. The cost of FACTS devices are high and therefore care must be taken while selecting their position and number of devices. With a view to reduce the cost of FACTS devices only, TCSC alone is considered but the results obtained are encouraging one.

Problem Formulation

Reactive Reserves

The different reactive power sources of a power system are synchronous generators and shunt capacitors. During a disturbance or contingency the real power demand does not change considerably but reactive power demand increases dramatically. This is due to increased voltage decay with increasing line losses and reduced reactive power generation from line charging effects. Sufficient reactive power reserve should be made available to supply the increased reactive power demand and hence improve the voltage stability limit.

The reactive power reserve of a generator is how much more reactive power that it can generate and it can be determined from its capacity curves [1].Simply speaking, the reactive power reserve is the ability of the generators to support bus voltages under increased load condition or system disturbances. The reserves of reactive sources can be considered as a measure of the degree of voltage stability.

Model of TCSC

TCSC is a series compensation component which consists of a series capacitor bank shunted by thyristor controlled reactor. The basic idea behind power flow control with the TCSC is to decrease or increase the overall lines effective series transmission impedance, by adding a capacitive or inductive reactance correspondingly. The TCSC is modeled as variable reactance, where the equivalent reactance of line X_{ij} is defined as:

$$X_{ij} = -0.8X_{Line} \leq X_{TCSC} \leq 0.2X_{Line} \tag{1}$$

where, X_{line} is the transmission line reactance, and X_{TCSC} is the TCSC reactance. The level of the applied compensation of the TCSC usually varies between 20% inductive and 80% capacitive (1).

Objective Function

The goal of optimal reactive power planning is to minimize the reactive power generation and reactive power loss by optimal positioning of TCSC and its corresponding parameters. Hence, the objective function can be expressed as

$$\mathrm{F} = \mathrm{Min}\left\{\mathrm{P_{Loss}} + \mathrm{Q_{Loss}} + \mathrm{Q_{Gen}} + \lambda \mathrm{V_{Lim}}\right\} \tag{2}$$

The terms in the objective function are:

$$P_{Loss} = \sum_{K=1}^{N_L} G_K \left[V_i^2 + V_j^2 - 2V_iV_j \cos\left(\delta_i - \delta_j\right) \right] \tag{3}$$

$$Q_{Loss} = \sum_{k=1}^{N_L} Q_{kLoss} \tag{4}$$

$$Q_{Gen} = \sum_{k=1}^{N_G} Q_{kGen} \tag{5}$$

$$V_{Lim} = \frac{\sum_{k=1}^{N_{PQ}} \left(V_k - V_k^{Lim} \right)}{\left(V_k^{Max} - V_k^{Min} \right)} \tag{6}$$

where P_{Loss} is the total system real power loss; Q_{Loss} is the total reactive power loss; Q_{Gen} is the total reactive power generated by generators; the fourth term in the objective function is the normalized violation of load bus (also known as 'PQ bus') voltage, V_i; N_L is the number of transmission lines; N_{PQ} and N_G are the number of load buses and generator buses respectively; λ is the penalty coefficient and set to 10.

Subject to Equality constraints

$$P_{Gi} - P_{Di} - \sum_{j=1}^{N_B} V_i V_{ij} Y_{ij} \left(X_{TCSC} \right) \cos\left(\delta_{ij} + \gamma_j - \gamma_i \right) = 0 \tag{7}$$

$$Q_{Gi} - Q_{Di} - \sum_{j=1}^{N_B} V_i V_{ij} Y_{ij} \left(X_{TCSC} \right) \sin\left(\delta_{ij} + \gamma_j - \gamma_i \right) = 0 \tag{8}$$

Inequality constraints

$$X_{TCSC}^{Min} \le X_{TCSC} \le X_{TCSC}^{Max} \tag{9}$$

$$V_i^{min} \le V_1 \le V_j^{max} \tag{10}$$

Implementation of PSO Algorithm

PSO is an evolutionary computation technique developed by Eberhart and Kennedy in 1995, and was inspired by the social behavior of bird flocking and fish schooling [24]. PSO has its roots in artificial life and social psychology as well as in engineering and computer science. It utilizes a population of individuals, called particles, which fly through the problem hyperspace with some given initial velocities. In each iteration, the velocities of the particles are stochastically adjusted considering. the historical best position of the particles and their neighborhood best position; where these positions are determined according to some predefined fitness function. Then, the movement of each particle naturally evolves to an optimal or near-optimal solution.

Each particle keeps track of its coordinates in the problem space which are associated with the best solution (fitness) it has achieved so far. The fitness value is also stored. This value is called P_{best}. When a particle takes all the population as its topological neighbors, the best value is a global best and is called G_{best}. After finding the two best values, the particle updates its velocity and positions with following equation (11) and (12).

$$V_i^{k+1} = W * V_i^k + C_1 * rand_1 * \left(P_{best\ i} - S_i^k\right) + C_2 * rand_2 * \left(G_{best} - S_i^k\right) \qquad (11)$$

$$S_i^{k+1} = S_i^k + V_i^{k+1} \qquad (12)$$

V_i^k= Velocity of agent i at kth iteration

V_i^{k+1}= Velocity of agent i at (k +1)th iteration

W = The inertia weight

$C_1 = C_2$ = individual and social acceleration constants (0 to 3)

$rand_1$=$rand_2$=random numbers (0 to1)

S_i^k = Current position of agent i at kth iteration

S_i^{k+1}= Current position of agent i at (k+1)th iteration

$P_{best\ i}$ = Particle best of agent i

G_{best} = Global best of the group

Particle Definition

Each particle is defined as a vector containing the TCSC line location number and its size.

Particle: [@ Φ]

Where

@ : is the TCSC line location number.

Φ: is the TCSC size.

PSO Parameters

The performance of the PSO is greatly affected by its parameter values. Therefore, a way to find a suitable set of parameters has to be chosen. In this case, the selection of the PSO parameters follows the strategy of considering different values for each particular parameter and evaluating its effect on the PSO performance. The optimal values for the PSO parameters are shown in Table I.

Number of particles

There is a trade-off between the number of particles and the number of iterations of the swarm and each particle fitness value has to be evaluated using a power flow solution at each iteration, thus the number of particles should not be large because computational effort could increase dramatically. Swarms of 5 and 25 particles are chosen as an appropriate population sizes.

Inertia weight

The inertia weight is linearly decreased. The purpose is to improve the speed of convergence of the results by reducing the inertia weight from an initial value of 0.9 to 0.1 in even steps over the maximum number of iterations as shown in (13).

$$W_{iter} = 0.9 - 0.8\left(\frac{iter - 1}{\max iter - 1}\right) \qquad (13)$$

Where W_{iter} is the inertia weight at current iteration.

iter is the current iteration number.

Maxiter is the maximum number of iterations.

Acceleration constants

A set of three values for the individual acceleration constants are evaluated to study the effect of giving more importance to the individual's best or the swarm's best: $c1 = \{1.5, 2, 2.5\}$. The value for the social acceleration constant is defined as: $c2 = 4 - c1$.

Number of Iterations

Different numbers of iterations {10, 25, 50} are considered in order to evaluate the effect of this parameter on the PSO performance.

Values for maximum velocity

In this case, for each particle component, values for the maximum velocity have to be selected. Based on previous results, a value of 7 is considered as the maximum velocity for the location line number.

Feasible region Definition

There are several constraints in this problem regarding the characteristics of the power system and the desired voltage profile. Each of these constraints represents a limit in the search space; therefore the PSO algorithm has to be programmed so that the particles can only move over the feasible region. For instance, the network in Fig. 2 has 4 transmission lines with tap changer transformer. These lines are not considered for locating TCSC, leaving 37 other possible locations for the TCSC. In terms of the algorithm, each time that a particle's new position includes a line with tap setting transformer, the position is changed to the geographically closest line (line without transformer). Finally, in order to limit the sizes of the TCSC units, the restrictions of level of compensation is applied to the particles.

Optimal Parameter Values

Table 1: Optimal values of PSO parameters.

Parameter	Optimal values
Number of particles	20
Inertia weight	Linearly decreased
Individual acceleration constant	2.5
Social acceleration constant	2.0
No of iterations	25
Velocity bounds	{-3,7}
$rand_1$	0.3
$rand_2$	0.2

Integer PSO

For this particular application, the position of the particle is determined by an integer number (line number). Therefore the particles' movement given by (2) is approximated to the nearest integer numbers. Additionally, the location number must not be a line with tap setting transformer. If the location is line with tap setting transformer, then the particle component regarding position is changed to the geographically closest line without a line.

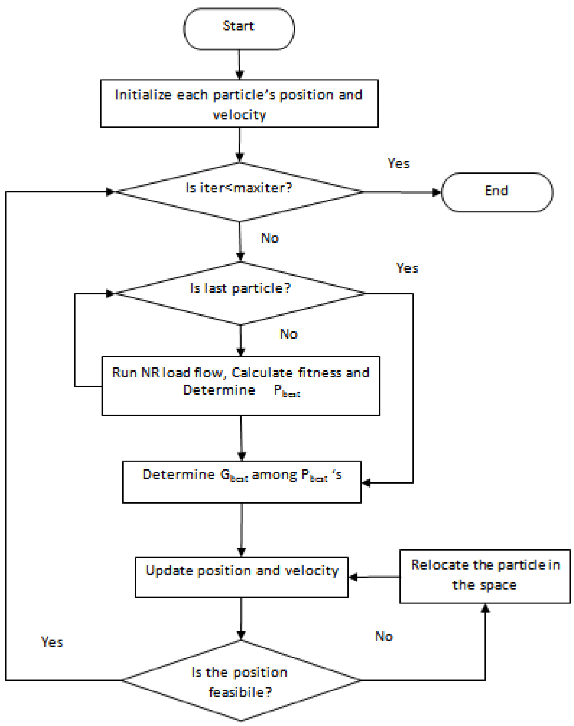

Figure 1: Flow chart for the implemented PSO.

Numerical Results and Discussions

The optimal reactive power flow control is formulated with the primary objective of minimization of reactive power generation and secondary objective of minimization of reactive power loss subject to voltage limit and reactive power limit constraints (2). The effectiveness of proposed approach has been illustrated using the IEEE 30 bus test system [25].

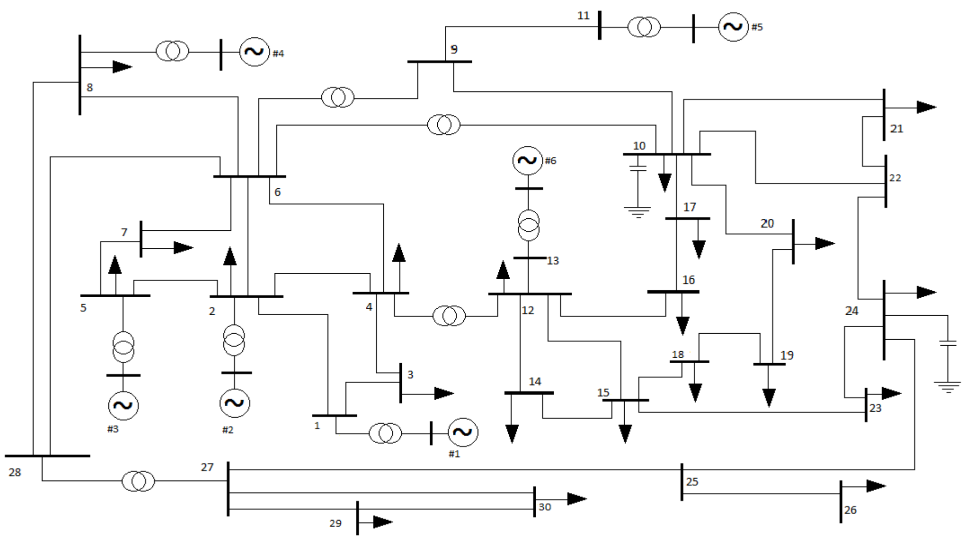

Figure 2: One line diagram of IEEE 30 Bus System.

The system has 6 generator buses, 24 load buses and 41 transmission lines. Transmission lines 11, 12, 15, and 36 are with tap changer transformers and therefore are not suitable for positioning of TCSC. Only the remaining 37 lines are considered as candidate locations for positioning of TCSC.

TCSC device is installed on different branches one by one based on the proposed algorithm. The objective function (2), with reactive power generation, real power loss, reactive power loss, and normalized violations of load bus voltage is solved by the proposed algorithm to locate TCSC in the most suitable line. The optimal location, which is the location at which value of objective function is the minimum, is solved for two different cases. The value of objective function is affected by the level of compensation, and for some values of level of compensation, power flow solution diverges giving worst solutions. Hence the level of compensation plays an important role in the process of optimization due to its complex non linearity.

Case 1: System under normal condition

Normal system (No Outage) with increased loading condition is considered for reactive power flow control to improve the voltage stability limit. The TCSC device is located in the global best position (Line) to improve the voltage stability by controlling the reactive power flow through the transmission lines of the system. The reactive power flow control is achieved so that the total reactive power loss and reactive power generation are reduced. The values of reactive power generation, reactive power loss and real power loss before and after TCSC are compared in table 2. Reduction in reactive power generation is an indication that the system is relieved from the stressed condition. The amount of reactive power generation reduction can be seen as reactive power reserve and it may be used when the system enters into a highly stressed condition again.

Table 2: Reduction in Q_{gen}, Q_{loss}, P_{loss}

IEEE 30 Bus System	Total Reactive Power Generation	Total Reactive Power Loss	Total real Power Loss
Without TCSC	233.994	152.141	39.303
With TCSC	220.249	138.380	39.127

The global best position for this case for TCSC device to improve voltage stability limit by the control of reactive power flow is identified as line number 5.Table 3 shows the global best result parameters of position, new reactance and old reactance.

Table 3: Global best results.

Global best position	Level of compensation	Line reactance	
		X_{old}	X_{new}
Line 5	-0.4174	0.1953	0.1138

The voltage deviation is also minimized after the insertion of TCSC device at the global best position. Improvement in voltage profile is depicted in figure 3.

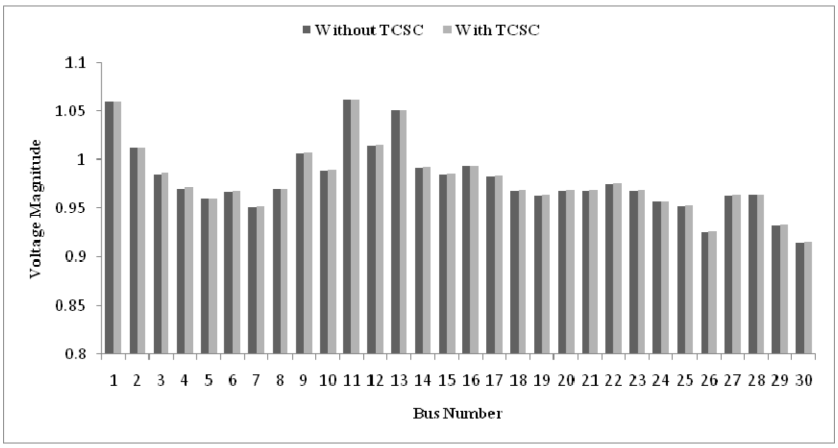

Figure 3: Voltage profile improvement.

Case 2: System under line outage contingency condition
Line outage contingency screening and ranking is carried out on the test system and the results are shown in table 4. The line outage is ranked according to the severity and severity is taken on the basis of increased reactive power generation and real power losses. It is clear from the table that outage of line number 5 is the most critical line outage and this condition is considered for voltage stability improvement.

Table 4: Contingency Ranking.

Rank	Outaged Line No	Total P_{loss} MW	Total Q_{gen} MVAR
1	5	80.554	352.866
2	2	63.492	309.035
3	4	62.301	304.707
4	7	47.986	267.767
5	6	46.040	263.012

The most suitable location for TCSC to control reactive power flow is found to be line number 10.The reduction in reactive power generation; reactive power loss and real power loss are obvious from the table 5. The reduction in all the three parameters is really encouraging.

T able 5: Reduction in Q_{gen},Q_{loss},$P_{loss.}$

IEEE 30 Bus System	Total Reactive Power Generation	Total Reactive Power Loss	Total real Power Loss
Without TCSC	352.866	270.259	80.554
With TCSC	342.772	260.880	78.160

The global best position for location of TCSC under contingency condition to improve voltage stability limit by the control of reactive power flow is identified as line number 10.Table 6 shows the global best result parameters of position, new reactance and old reactance.

Table 6: Global best results.

Global best position	Level of compensation	Line reactance	
		X_{old}	X_{new}
Line 10	-0.6836	0.0420	0.0133

The bus voltage deviation is also minimized after the installation of TCSC device and the resultant Improvement in voltage profile is illustrated in figure 4. It is clear from the figure that the voltage profile is improved considerably. In this case both the real power loss minimization and voltage profile improvement are better. A power system is with increased real power loss and decreased bus voltage magnitudes especially during disturbance/contingency condition (under highly stressed condition).The much reduction in real power loss and increase in voltage magnitudes after the insertion of TCSC proves that FACTS devices are highly efficient in relieving a power network from stressed condition and improving voltage stability improvement.

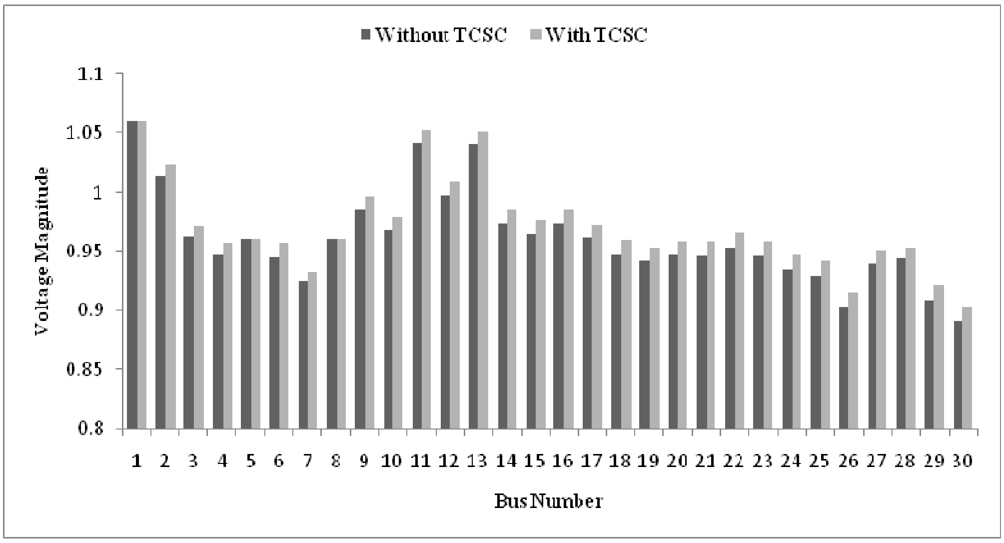

Figure 4: Voltage profile improvement.

Conclusions

This work demonstrates the application of the Particle Swarm Optimization method to solve the problem of optimal placement and sizing of a TCSC device in a medium size power network for voltage stability limit improvement by controlling the reactive power flow and reducing the reactive power generation. It is clear from the simulation results that TCSC device is good at controlling the reactive power flow through different transmission lines of the system and it results in reduced reactive power generation. The reduction in reactive power generation can be used as reactive power reserve when the system needs it again. That is the system is left with reactive capability and thereby under voltage secured condition. The algorithm is easy to implement and it is able to find multiple optimal solutions to this constrained multi-objective problem, giving more flexibility to take the final decision about the location and size of the TCSC unit. The settings of the PSO parameters are shown to be optimal for this type of application; the algorithm is able to find the optimal solutions with a relatively small number of iterations and particles, therefore with a reasonable computational effort.

References

[1] C. W. Taylor, Power System Voltage Stability. New York: McGraw-Hill, 1994P.

[2] Kessel and H. Glavitsch, "Estimating the Voltage Stability of Power System," IEEE Trans. Power delivery, Vol. PWRD-1, No. 3, pp. 346- 354, July 1986.

[3] H. Wan, J. D. Mc Calley and V. Vittal, “Risk Based Voltage Security Assessment”, IEEE Transaction on Power Systems, Vol. 15, No. 4, Nov. 2000, pp. 1247 – 1254.

[4] T. Menezes, L. C. da Silva, and V. F. da Costa, “Dynamic VAR sources scheduling for improving voltage stability margin,” IEEE Trans. Power Systems., vol. 18, no. 2, pp. 969–971, May 2003.

[5] S. Granville, “Optimal reactive dispatch through interior point methods,” IEEE Trans. Power Syst., vol. 9, no. 1, pp. 136–146, Feb. 1994.

[6] E. Vaahedi, Y. Mansour, C. Fuchs, S. Granville, M. D. L. Latore, and H. Hamadanizadeh, “Dynamic security constrained optimal power flow/var planning,” IEEE Trans. on Power Systems, vol. 16, no. 1, pp. 38–43, Feb. 2001.

[7] Lee, K. Y. and Yang, F. F. , “Optimal Reactive Power Planning Using Evolutionary Algorithms :A Comparative Study for Evolutionary Programming, Evolutionary Strategy, Genetic Algorithm and Linear Programming”, IEEE Transactions on power systems, Vol. 13, No. 1, Feb-1998, pp : 101-108.

[8] C. W. Liu, C. S. Chang and J. A. Jiang, “Genetic Algorithms as a Reactive Power Dispatching Aid for Voltage Security Enhancement”, Proc. Natl.Sci. Counc. ROC (A), Vol.25, No. 1, 2001., pp.53 – 62.

[9] J. Cao and Q. H. Wu, “Optimal Reactive Power Dispatch Using an Adaptive Genetic Algorithm”, Genetic Algorithms In Engineering Systems:Innovations And Applications,1997. GALESIA97 Second International Conference On (Conf.Publ. No. 446), 2 - 4 Sept. 1997, p.p. 117 – 122

[10] Q. H. Wu and J. T. Ma, “Power system optimal reactive power dispatch using evolutionary programming”, IEEE Transaction on Power Systems, Vol. 10, Issue 3, Aug. 1995, pp. 1243 – 1249.

[11] M. Z. M. Idrus, I. Musirin and Z. Zainuddin, “BiologicalComputing Technique for Optimal Reactive Power Dispatch”, Colloqium on Signal Processing and its Application CSPA 2006, 11 – 13 March 2006 Pahang, Malaysia, pp. 112 - 118.

[12] H. Yoshida, K.Kawata, Y.Fukuyama, S.Takayama and Y.Nakanishi, "A particle swarm optimization for reactive power and voltage control considering voltage security assessment," IEEE Trans.on Power Systems, vol.15, pp. 1232-1239, 2000.

[13] Feng Dong,et al, “Improving Voltage Stability by Reactive Power Reserve Management” IEEE transactions on Power Systems, Vol. 20,N0.1, pp.338-345, February 2005.

[14] Noroozian M. Angquist L., Ghandhari M., Andersson G. "Improving Power System Dynamics by Series-Connected FACTS Devices", IEEE Transactions on Power Delivery, vol. 12, No. 4, pp.1635-1641, October 1997.
[15] Wood A.J. and Wollenberg B.F. "Power Generation, Operation, and Control", John Wiley and Sons, New York, 1996.
[16] N G. Hingorani, L. Gyugyi, Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems, IEEE Press, New- York, 2000.
[17] Lu Yunqiang and Abur Ali,: "Improving System Static Security via Optimal Placement of Thyristor Controlled Series Capacitor (TCSC)", IEEE, PES, WM, Columbus, Ohio, USA., Jan. 2001.
[18] Billinton R., Firuzabad M.F., Faried S.O. "Power System Reliability Enhancement using a thyristor Controlled Series Capacitor", IEEE transactions on Power Systems vol.14, No. 1, pp.369-374, February. 1999.
[19] Preecha Preedavichit, Srivastava, S. C., "Optimal Reactive Power Dispatch Considering FACTS Devices", Electric power system research, Vol. 46, 1998, pp : 251-257.
[20] J. J. Jimenez-Nunez and J.R. Cedeno-Maldonado, "A Particle Swarm Optimization Approach for Reactive Power Dispatch", Power Symposium, 2005. Proceedings of the 37th Annual North American, 23-25 Oct. 2005, pp 198 – 205.
[21] Paserba, N.Miller, E.Laesen and R.Piwko," A Thyristor controlled series compensation model for power system stability analysis," IEEE.
[22] Garng Huang and Tong Zhu, "TCSC as a transient voltage stabilizing controller," IEEE conference proceedings, pp.628-633., 2001.
[23] Yunqiang Lu, Ali Abur, "Static security enhancement via optimal utilization of Thyristor-Controlled Series Capacitors," IEEE Trans.Power Systems., vol.17, pp.324-329, May 2002.
[24] J. Kennedy, R. Eberhart, "Particle swarm optimization in," Proceedings of the IEEE International Conference on Neural Networks, pp. 1942- 1948 1995.
[25] Power Systems Test Case, The University of Washington Archive, http://www.ee.washington.edu/research/pstca/, 2000.

Biographies


S. Sakthivel received the Degree in Electrical and Electronics Engineering and Masters Degree in Power Systems Engineering in 1999 and 2002 respectively. He is doing the Ph.D., Degree in Electrical Engineering faculty from Anna University of Technology, Coimbatore, India. He is working as an assistant professor of Electrical and Electronics Engineering at V.R.S. College of Engineering and Technology, Villupuram, Tamil Nadu, India. His research areas of interest are Power System control, Optimization techniques, FACTS and voltage stability improvement.


Dr. D. Mary received the Ph.D. Degree from Bharathiyar University, Tamil Nadu, India in 2002. She is the Professor and Head of the Department of Electrical and Electronics Engineering, Government College of Engineering, Bargur, Tamil Nadu, India. Power System Control and Instrumentation and Intelligent Techniques are some of her areas of interest. She has published more than 50 technical papers in leading international ‘research journals.