Particle Swarm Optimization Algorithm for Voltage Stability Enhancement by Optimal Reactive Power Reserve Management with Multiple TCSCs

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ABSTRACT
A power system, during disturbances, is at risks of voltage instability due to insufficient reactive power reserves. Reactive power reserve management is a reliable indicator of voltage security of power networks. This paper proposes a Particle Swarm Optimization (PSO) based optimal reactive power reserve management task incorporating only one type of FACTS device. Optimal placement of multi type FACTS devices can naturally manage the reactive power reserves. 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 multiple TCSCs is considered for an acceptable and suboptimal solution for reactive power reserve management. Particle swarm optimization technique optimizes the location and size of TCSCs.The effectiveness of the proposed work is tested for IEEE-30 Bus test system with multiple TCSC devices. It has also been observed that the proposed algorithm can be applied to larger systems and do not suffer with computational difficulties.

Keywords
FACTS devices, TCSC, Reactive Power Reserve Management and Particle Swarm Optimization Algorithm.

1. INTRODUCTION
The present day power systems are forced to be operated closer to stability margins 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 a power system to find the possible ways to improve the voltage stability. 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 power injection from generators and synchronous condensers with the aim of improving the voltage stability margin. This method is formulated based on modal participation factors and an optimal power flow (OPF) wherein the voltage stability margin, as computed from eigenvectors of a reduced Jacobian, is maximized by reactive power 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 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 power 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 reserve management 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 etc.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.

2. PROBLEM FORMULATION

2.1 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 reserves 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 power sources can be considered as a measure of the degree of voltage stability.

2.2 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

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

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).

2.3 Objective Function

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

$$F\left(U\right) = \text{Min}\left(Q_{Loss} + Q_{Gen} + \lambda_1 V_{Lim} + \lambda_2 Q_{Lim}\right) \qquad 2$$

The terms in the objective function are:

$$Q_{Loss} = \sum_{k=1}^{N_L} Q_{kLoss} \qquad 3$$

$$Q_{Gen} = \sum_{k=1}^{N_G} Q_{kGen} \qquad 4$$

$$V_{Lim} = \frac{\sum_{k=1}^{N_{PQ}} \left(V_k - V_k^{Lim}\right)}{V_k^{Max} - V_k^{Min}} \qquad 5$$

$$Q_{Lim} = \sum_{k=1}^{N_G} \left(Q_k - Q_k^{Lim}\right) \Big/ \left(Q_k^{Max} - Q_k^{Min}\right) \qquad 6$$

where Q_{Loss} is the total reactive power loss;Q_{Gen} is the total reactive power generated by generators; the third and fourth terms in the objective function are normalized violations of load bus (also known as 'PQ bus') voltages, V_k, and generator reactive power outputs, Q_k respectively; and N_L the number of transmission lines; N_{PQ} and N_G are the number of load buses and generator buses respectively; λ_1 and λ_2 are penalty coefficients and set to 10 and V^{Lim} and Q^{Lim} denote the violated upper or lower limit respectively, which are defined as:

$$V_k^{Lim} = \begin{cases} V_k^{Max} & \text{if} \quad V_k > V_k^{Max} \\ V_k^{Min} & \text{if} \quad V_k < V_k^{Min} \end{cases}$$

$$Q_k^{Lim} = \begin{cases} Q_k^{Max} & \text{if} \quad Q_k > Q_k^{Max} \\ Q_k^{Min} & \text{if} \quad Q_k < Q_k^{Min} \end{cases} \qquad 7$$

Subject to:

Equality constraints

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

$$Q_{Gi} - Q_{Di} - \sum_{j=1}^{N_B} V_i V_{ij} Y_{ij}\left(X_{TCSC}\right)\sin\left(\delta_{ij} + \gamma_j - \gamma_i\right) = 0 \qquad 9$$

Inequality constraint

$$X_{TCSC}^{Min} \le X_{TCSC} \le X_{TCSC}^{Max} \qquad 10$$

2.4 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 position according to the following equations (11) and (12).

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

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

V_i^k= Velocity of agent i at k^{th} iteration

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

W_k = 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 = Position of agent i at k^{th} iteration

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

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

G_{best} = Global best of the group

2.4.1 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.

2.4.2 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.1.

2.4.3 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 20 particles are chosen as an appropriate population sizes.

2.2.4 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).

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

Where W_k is the inertia weight at iteration *k*.
iter: is the iteration number(k).
Maxiter: is the maximum number of iterations.

2.2.5 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: C_1 = {1.5, 2, 2.5}. The value for the social acceleration constant is defined as: $C_2 = 4.5 - C_1$.

2.4.6 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.

2.4.7 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.

2.4.8 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.

2.4.9 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	50
Velocity bounds	{-3,7}
$rand_1$	0.3
$rand_2$	0.2

2.4.10 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 number. 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.

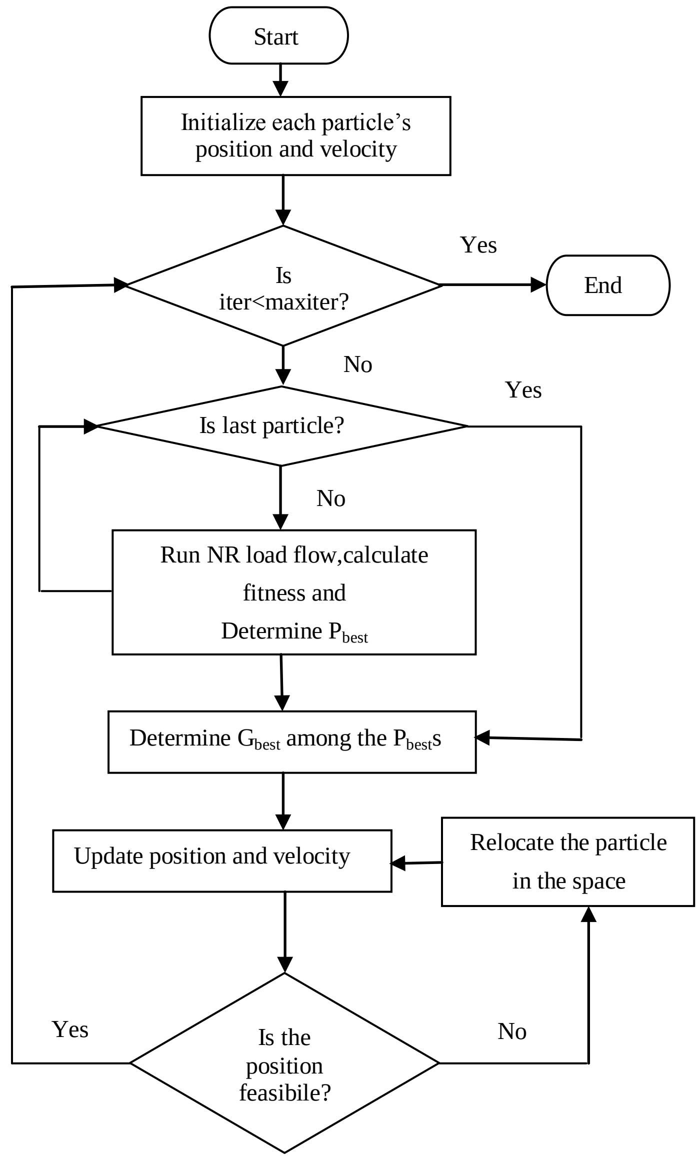

Fig .1. Flow chart for PSO

3. NUMERICAL RESULTS AND DISCUSSIONS

The optimal reactive power reserve management is formulated with the primary objective of minimization of reactive power generation and secondary objective of minimization of reactive.

The objective function (2), with reactive power generation, reactive power losses, normalized violations of load bus voltage and reactive power generation limits, is solved by the proposed algorithm to locate TCSC in the most suitable line.

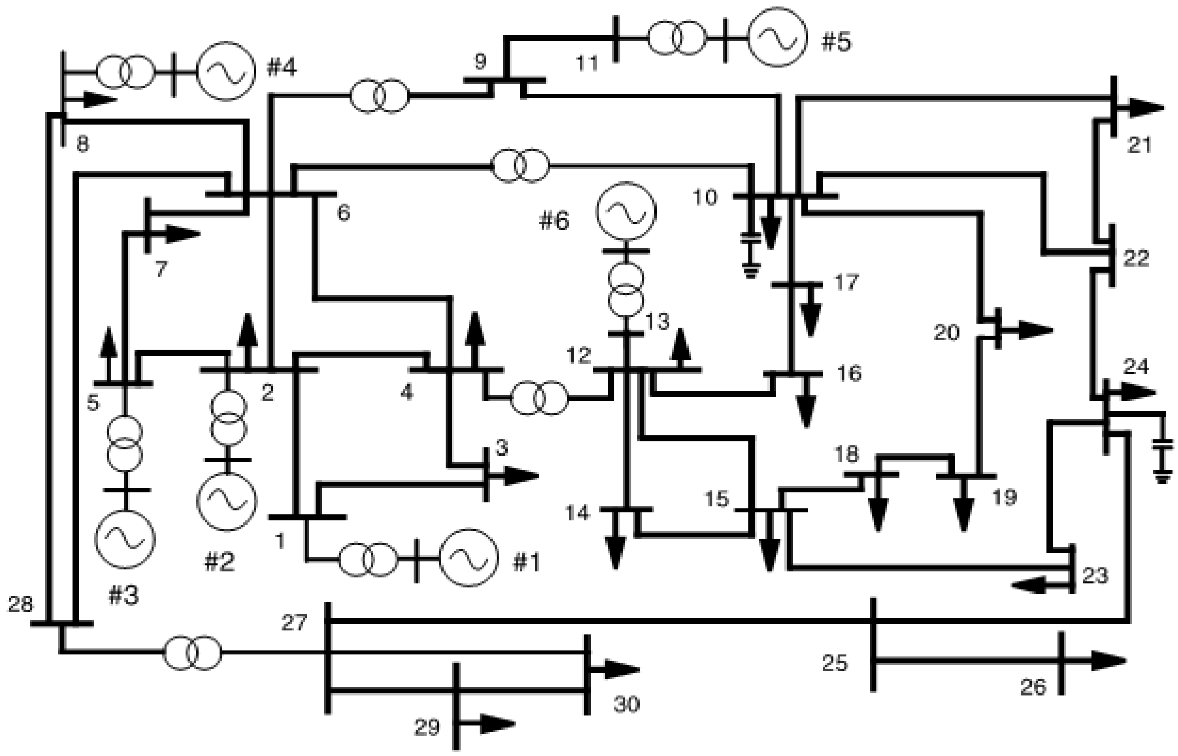

Fig. 2. Single-line Diagram of IEEE 30-bus System.

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].

The system (Fig.2) has 6 generator buses 24 load buses and 41 branches. TCSC device is installed on different branches one by one based on the proposed algorithm and further the model has been applied to multiple TCSC devices (two and three).

The optimal location, which is the location at which the value of objective function is minimum, can be found as line no 2. That means locating a TCSC in this line gives best optimum value for the objective function. 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.

Table. 2.

TCSC Position and Reduction in Total Q_{loss}

IEEE 30 Bus system	Line No	Line Reactance		Q_{Loss} in MVAR
		With TCSC	Without TCSC	
Without TCSC	----	----	----	68.691
With 1 TCSC	2	0.08274	0.1652	61.661

With 2 TCSCs	2 5	0.10796	0.1953	55.488
With 3 TCSCs	2 5 1	0.03255	0.0575	50.063

TCSC device locations have been solved for optimal solutions and reduction in reactive power loss are tabulated in Table 2. It can be observed that the reduction in reactive power loss by implementation of the proposed algorithm with one, two and three TCSC devices shows the maximum improvement.

When only one TCSC is incorporated, the Q_{Loss} reduction is from 68.691 MVAR to 61.661MVAR, which is about 10%.For two TCSCs the reduction is about 19% and it is about 27% when three TCSCs are considered. The total reactive power loss in the system with and without installation of TCSCs is illustrated in Fig.3

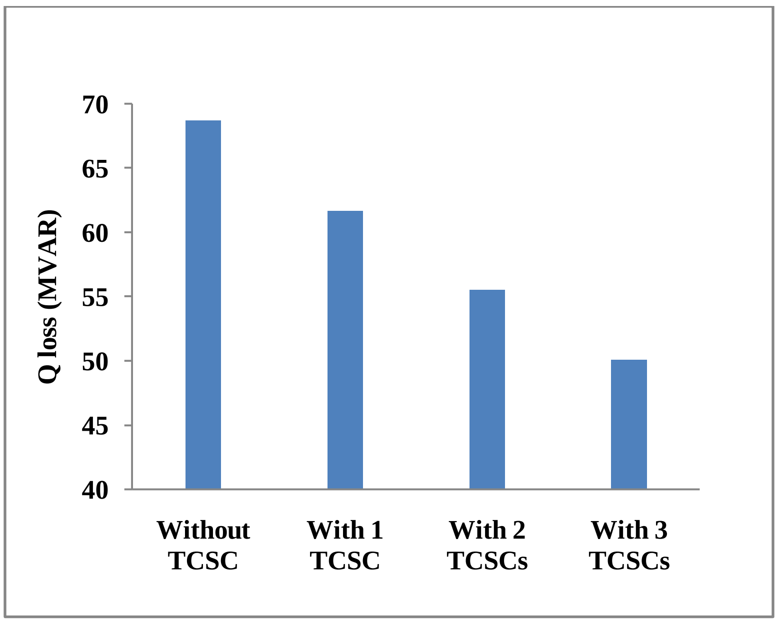

Fig. 3 Reduction in Total Q loss

The reactive power generation, before and after positioning of TCSC, from all 6 generator buses and 2 SVC buses (bus10 and bus 24) are tabulated in Table III. Buses 10 and 24 are not considered for minimization of reactive power generation and therefore there is no change in Qgen at those buses. Therefore the candidate buses considered for reactive power generation reduction are only the generator buses of 1,2,5,8,11 and 13.When three TCSCs are used, reactive power generation is reduced from 146.924 MVAR to 128.534 MVAR (about 13%).

That is the reactive power reserve is increased by 13%, making the system more voltage secured in terms of additional capability of generators to generate more reactive power during disturbance/contingency. In addition to the principle objective of reactive power reserve management, the three TCSC locations (lines 2,5 and 1) that are major power transmitting channels in the IEEE 30 Bus test system are expected to be with increased power handling capacity as the effective reactance of the line is reduced.

Table.3.

Reactive Power Generation at Different Buses

Gen bus No	Qgen Without TCSC in MVAR	Qgen With '1' TCSC in MVAR	Qgen With '2' TCSCs in MVAR	Qgen With '3' TCSCs in MVAR
1.	-17.140	-22.185	-22.406	-8.658
2.	47.709	43.923	39.016	14.721
5.	35.893	36.145	36.660	33.649
8.	30.655	31.719	30.521	37.445
10.	19.000	19.000	19.000	19.000
11.	16.265	16.444	16.279	16.951
13.	10.243	10.522	10.339	11.125
24.	4.300	4.300	4.300	4.300
Total Qg	146.924	139.868	133.708	128.534

Total reactive power generation (Qgen) from all the generator buses is shown in Fig.4. It is observed from the plot that the reduction in Ggen is encouraging and voltage stability of the system is ensured.

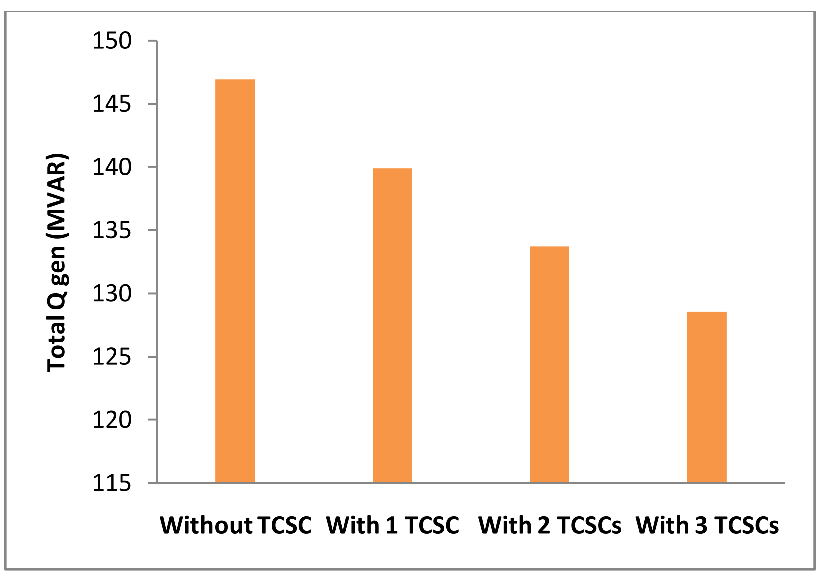

Fig. 4. Reduction in Total Q generation

4. CONCLUSIONS AND FUTURE WORK

This study shows step by step application of the Particle Swarm Optimization method to solve the problem of optimal placement and sizing of multiple TCSC units in a medium size power network. 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 sizes of the TCSC units. 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, hence with a reasonable computational effort.

The simulation results show that multiple TCSCs can be used for improving voltage security margin by leaving sufficient amount of reactive reserves at generator buses. The security margin increases with the number of TCSCs but there should be a limit on the number of devices due to economic reasons. The results are promising for the medium size power network used as an example. For large power systems, the PSO algorithm could have a significant advantage compared to exhaustive search and other methods by giving better solutions with less computational effort. Future work can be done by testing the algorithm on larger power systems and including other types of FACTS devices.

5. REFERENCES

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

[2] P. 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 Syst., 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.Trans.on Power-Delivery, vol. 10, pp.1471-1478, 1995.

[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., p.p.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 itsApplication 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 proceeding, pp.628-633., 2001.

[23] Yunqiang Lu, Ali Abur, "Static security enhancement via optimal utilization of Thyristor-Controlled Series Capacitors," IEEE Trans.Power System., 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.

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