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

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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:

\[
X_{ij} = -0.8X_{\text{Line}} \leq X_{\text{TCSC}} \leq 0.2X_{\text{Line}}
\]

where, \( X_{\text{Line}} \) is the transmission line reactance, and \( X_{\text{TCSC}} \) 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

\[
F = \text{Min} \left\{ P_{\text{Loss}} + Q_{\text{Loss}} + Q_{\text{Gen}} + \lambda V_{\text{Lim}} \right\}
\]
The terms in the objective function are:

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

(3)

\[
Q_{\text{Loss}} = \sum_{k=1}^{N_L} Q_{k\text{Loss}}
\]

(4)

\[
Q_{\text{Gen}} = \sum_{k=1}^{N_G} Q_{k\text{Gen}}
\]

(5)

\[
V_{\text{Lim}} = \frac{\sum_{k=1}^{N_{PQ}} (V_k - V_{k\text{Lim}})}{(V_{k\text{Max}} - V_{k\text{Min}})}
\]

(6)

where \( P_{\text{Loss}} \) is the total system real power loss; \( Q_{\text{Loss}} \) is the total reactive power loss; \( Q_{\text{Gen}} \) 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; \( \lambda \) is the penalty coefficient and set to 10.

**Subject to Equality constraints**

\[
P_{\text{Gi}} - P_{\text{Di}} - \sum_{j=1}^{N_{PQ}} V_iV_j Y_{ij} (X_{TCSC}) \cos(\delta_{ij} + \gamma_j - \gamma_i) = 0
\]

(7)

\[
Q_{\text{Gi}} - Q_{\text{Di}} - \sum_{j=1}^{N_{PQ}} V_iV_j Y_{ij} (X_{TCSC}) \sin(\delta_{ij} + \gamma_j - \gamma_i) = 0
\]

(8)

**Inequality constraints**

\[
X_{\text{TCSC}}^{\text{Min}} \leq X_{\text{TCSC}} \leq X_{\text{TCSC}}^{\text{Max}}
\]

(9)

\[
V_i^{\text{min}} \leq V_i \leq V_i^{\text{max}}
\]

(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).

$$
V_i^{k+1} = w \cdot V_i^k + c_1 \cdot \text{rand}_1 \cdot (P_{best_i} - S_i^k) + c_2 \cdot \text{rand}_2 \cdot (G_{best} - S_i^k) \tag{11}
$$

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

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

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

$w$ = The inertia weight

$c_1, c_2$ = individual and social acceleration constants (0 to 3)

$\text{rand}_1, \text{rand}_2$ = random numbers (0 to 1)

$S_i^k$ = Current position of agent $i$ at $k^{th}$ 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.

$\text{Particle: } [@ \Phi]$

Where

$@$ : is the TCSC line location number.

$\Phi$ : 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).

\[ W_{\text{iter}} = 0.9 - 0.8 \left( \frac{\text{iter} - 1}{\text{max iter} - 1} \right) \]  

(13)

Where \( W_{\text{iter}} \) is the inertia weight at current iteration.
\( \text{iter} \) is the current iteration number.
\( \text{Maxiter} \) 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.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Optimal values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of particles</td>
<td>20</td>
</tr>
<tr>
<td>Inertia weight</td>
<td>Linearly decreased</td>
</tr>
<tr>
<td>Individual acceleration constant</td>
<td>2.5</td>
</tr>
<tr>
<td>Social acceleration constant</td>
<td>2.0</td>
</tr>
<tr>
<td>No of iterations</td>
<td>25</td>
</tr>
<tr>
<td>Velocity bounds</td>
<td>{-3,7}</td>
</tr>
<tr>
<td>rand₁</td>
<td>0.3</td>
</tr>
<tr>
<td>rand₂</td>
<td>0.2</td>
</tr>
</tbody>
</table>

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.

![Flow chart for the implemented PSO.](image)

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].

![One line diagram of IEEE 30 Bus System.](image)

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
Voltage Stability Limit Improvement

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>
<thead>
<tr>
<th>IEEE 30 Bus System</th>
<th>Total Reactive Power Generation</th>
<th>Total Reactive Power Loss</th>
<th>Total Real Power Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without TCSC</td>
<td>233.994</td>
<td>152.141</td>
<td>39.303</td>
</tr>
<tr>
<td>With TCSC</td>
<td>220.249</td>
<td>138.380</td>
<td>39.127</td>
</tr>
</tbody>
</table>

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>
<thead>
<tr>
<th>Global best position</th>
<th>Level of compensation</th>
<th>Line reactance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line 5</td>
<td>-0.4174</td>
<td>X_{old} 0.1953</td>
</tr>
<tr>
<td></td>
<td></td>
<td>X_{new} 0.1138</td>
</tr>
</tbody>
</table>

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>
<thead>
<tr>
<th>Rank</th>
<th>Outaged Line No</th>
<th>Total P loss MW</th>
<th>Total Q gen MVAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>80.554</td>
<td>352.866</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>63.492</td>
<td>309.035</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>62.301</td>
<td>304.707</td>
</tr>
<tr>
<td>4</td>
<td>7</td>
<td>47.986</td>
<td>267.767</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>46.040</td>
<td>263.012</td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>IEEE 30 Bus System</th>
<th>Total Reactive Power Generation</th>
<th>Total Reactive Power Loss</th>
<th>Total real Power Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without TCSC</td>
<td>352.866</td>
<td>270.259</td>
<td>80.554</td>
</tr>
<tr>
<td>With TCSC</td>
<td>342.772</td>
<td>260.880</td>
<td>78.160</td>
</tr>
</tbody>
</table>

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>
<thead>
<tr>
<th>Global best position</th>
<th>Level of compensation</th>
<th>Line reactance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line 10</td>
<td>-0.6836</td>
<td>X_{old} 0.0420</td>
</tr>
<tr>
<td></td>
<td></td>
<td>X_{new} 0.0133</td>
</tr>
</tbody>
</table>

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

**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.

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