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# Enhancement of Total Transfer Capability by Particle Swarm Optimization

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**Abstract:** *In this paper, a Particle Swarm Optimization (PSO) based algorithm has been suggested to find the optimal location and setting of Thyristor Controlled Series Compensator (TCSC) for simultaneously maximizing the Total Transfer Capability (TTC) and minimizing total real power losses of the competitive electricity markets having bilateral and multilateral transactions. While solving multi-objective optimal power flow, various inequality constraints are handled by penalty function. The robustness of the proposed algorithm has been tested on IEEE 30 bus and practical Uttar Pradesh State Electricity Board (UPSEB, India) 75 bus systems. PSO gives accurate results which may be used for online TTC calculation at the energy management centre.*

**Keywords:** *Particle swarm optimization, Thyristor controlled series compensator, Total transfer capability*

## 1. INTRODUCTION

Total Transfer Capability (TTC) is defined as the amount of electric power that can be transferred from one area to another over the interconnected transmission network in a reliable manner based on pre-contingency and post-contingency conditions [1]. In recent time, electrical supply systems of many countries have been transformed from monopolistic nature to competitive structure to increase efficiency, reliability, stability and to reduce cost. In this new era, there should be sufficient TTC to fulfill scheduled transactions between the buyers and sellers and to provide non-discriminatory open access to market participants. TTC and Available Transfer Capability (ATC)[1] are calculated between a pair of areas and they are posted on Open Access Same-time Information System to make competition effective.

Large increase in power demand, competition and scare natural resources are some factors due to which transmission systems operate very near to their thermal limits. But because of economic, environmental and political reasons it is not preferable to build new transmission lines. So there is an interest in better utilization of existing capacities of power system by installing Flexible A.C. Transmission System (FACTS) device such as Thyristor Controlled Series Compensator (TCSC) [2]. FACTS are the power electronics based converter-inverter circuits which can enhance TTC, voltage stability, loadability, security etc. and can reduce losses, cost of generation, can remove congestion and fulfill transaction requirement rapidly, dynamically and efficiently.

Due to the following two reasons it is necessary to “optimally” locate FACTS devices in order to obtain their full benefits. (1) They are costly devices, (2) They may have negative effects on system stability unless they are optimally placed [3].

### 1.1. Literature Survey

Various classical and artificial intelligent optimization methods have been proposed to maximize TTC/ATC with and without FACTS devices. G.C. Ejebe *et al.* [4] proposed continuation power flow for determining hourly TTC and ATC but It requires effective parameterization of predictor, corrector and step length to obtain solution. The computational effort required is large. It uses common loading factor to increase generation and load which may result in a conservative TTC. M.H.Gravener *et al.* [5] used repeated power flow method to determine ATC. It is simple method but it does not optimize generator output power and its voltage. K.S.Verma *et al.* [6] proposed sensitivity based approach to optimally locate FACTS devices to enhance TTC. Ying Xiao *et al.* [7] used predictor corrector primal duel interior point linear programming to enhance ATC using various FACTS devices. However it did not optimize their ratings and locations. M. Shaaban *et al.* [8] proposed SQP based method to find TTC incorporating the effect of reactive power but it requires the calculation of Hessian matrix in each iteration which is time consuming. Weixing Li *et al.* [9] used sequential quadratic programming to calculate probabilistic TTC considering different contingency states. But this method requires second order derivative of the objective function. P. Jirapong *et al.* [10] proposed hybrid evolutionary algorithm to optimally place multi-type FACTS devices to maximize TTC. M. Rashidinejad *et al.* [11] proposed real genetic algorithm to optimally locate two TCSC for enhancing ATC of IEEE 9 bus and 30 bus systems.

Venkatesh *et al.* [12] used PTDF for determining ATC and results are compared with NR method. A Kumar *et al.* [13] proposed bifurcation approach to determine ATC in the presence of SVC. S. Mollazei *et al.* [14] used modified PSO method to maximize TTC and to minimize voltage deviation using TCSC in 5 area test system.

From the literature survey it is revealed that with the inclusion of FACTS control variables, the "optimal placement of FACTS devices" becomes highly nonlinear and non-convex optimization problem which can not be effectively solved by the classical methods as they may get trapped into local minima or diverge at all.

To solve such problem, an artificial intelligent method called Particle Swarm Optimization [15] may be used as it is a fast method and it provides global solution. PSO has shown its superiority over other classical and AI methods with respect to execution time and global solution in solving economic dispatch problem [16] and optimal reactive power dispatch problem [17].

So in this article, PSO based algorithm has been suggested to find the best location and setting of TCSC to maximize TTC and to minimize losses of the competitive electricity markets consisting of bilateral and multilateral transactions under normal and contingency states. The IEEE 30 bus and practical Uttar Pradesh State Electricity Board (UPSEB, INDIA) 75 bus systems have been used to study the applicability of the PSO based algorithm.

This article has been organized as follows: Section 2 describes static modeling of TCSC. Section 3 includes multi-objective optimal power flow problem formulation. Section 4 includes mathematical modeling of Bilateral and Multilateral transactions. Section 5 explains overview of PSO method. In Section 6, PSO based algorithm to optimally locate TCSC for maximizing TTC value and minimizing losses has been included. Section 7 discusses simulation results and in Section 8 conclusive remarks have been given.

## 2. STATIC MODELING OF TCSC

As shown in Fig. 1, the TCSC has been represented by a variable capacitive/inductive reactance inserted in series with the transmission line [18]. So the reactance of the transmission line is adjusted by TCSC directly. Let, $X_{mn}$ is the reactance of the transmission line, $Xc$ is the reactance of TCSC and $X_{new}$ is the new reactance of the line after placing TCSC between bus $m$ and $n$. Mathematically, equation is written as:

$$X_{new} = X_{mn} - Xc \tag{1}$$

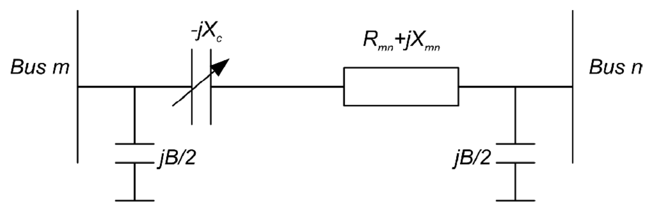


**Figure 1:** Equivalent Circuit of Transmission Line After Placing TCSC

The modified power flow equations of the transmission line in the presence of TCSC are given as below:

$$P_{mn} = V_m^{\,2} G_{mn} - V_m V_n (G_{mn}\cos\delta_{mn} + B_{mn}\sin\delta_{mn}) \tag{2}$$

$$Q_{mn} = -V_m^{\,2}\left(B_{mn} + \frac{B}{2}\right) - V_m V_n (G_{mn}\sin\delta_{mn} - B_{mn}\cos\delta_{mn}) \tag{3}$$

$$P_{nm} = V_n^{\,2} G_{mn} - V_m V_n (G_{mn}\cos\delta_{mn} - B_{mn}\sin\delta_{mn}) \tag{4}$$

$$Q_{nm} = -V_n^{\,2}\left(B_{mn} + \frac{B}{2}\right) + V_m V_n (G_{mn}\sin\delta_{mn} + B_{mn}\cos\delta_{mn}) \tag{5}$$

where,

$$G_{mn} = \frac{R_{mn}}{R_{mn}^{\,2} + (X_{mn} - X_c)^2},\; B_{mn} = \frac{-(X_{mn} - X_c)}{R_{mn}^{\,2} + (X_{mn} - X_c)^2}$$

$P_{mn}$, $Q_{mn}$: Active and reactive power flow from bus $m$ to $n$

$P_{nm}$, $Q_{nm}$: Active and reactive power flow from bus $n$ to $m$

$G_{mn}$: New line conductance between bus $m$ and $n$

$B_{mn}$: New line susceptance between bus $m$ and $n$

$R_{mn}$: Line resistance between bus $m$ and $n$

## 3. PROBLEM FORMULATION

### 3.1. Optimal Power Flow Model

A multi-objective optimal power flow given in [10] has been modified to optimally locate TCSC for maximizing TTC and minimizing total real power loss, subject to satisfy various equality and inequality constraints. The OPF is given in (6).

$$Max\{w_1 \times \sum_{m=1}^{LOAD\_SINK} P_{Dm} - w_2 \times \sum_{r=(m,n),r\in N_L}^{N_L} (P_{mn} + P_{nm}) - PF\} \tag{6}$$

Subject to the power balance equations (equality constraints)

$$\left\{\begin{aligned} P_{Gm} - P_{Dm} - \sum_{n=1}^{N_b} |V_m||V_n||Y_{mn}|\cos(\delta_m - \delta_n - \theta_{mn}) = 0 \\ Q_{Gm} - Q_{Dm} - \sum_{n=1}^{N_b} |V_m||V_n||Y_{mn}|\sin(\delta_m - \delta_n - \theta_{mn}) = 0 \end{aligned}\right\} \tag{7}$$

Various operating constraints (inequality constraints)

$$P_{Gm}^{\min} \le P_{Gm} \le P_{Gm}^{\max}, m\forall N_G \tag{8}$$

$$Q_{Gm}^{\min} \le Q_{Gm} \le Q_{Gm}^{\max}, m\forall N_G \tag{9}$$

$$|S_l| \le S_l^{\max},\ l\forall N_L \tag{10}$$

$$V_m^{\min} \le V_m \le V_m^{\max}, m\forall N_b \tag{11}$$

$$X_C^{\min} \le X_C \le X_C^{\max} \text{ p.u.} \tag{12}$$

where,

$w_1$, $w_2$ : Weighting coefficients in the range [0, 1] which indicate the relative importance of the conflicting objectives.

*LOAD_SINK* : Total number of load buses in sink area

$\sum_{m=1}^{LOAD\_SINK} P_{Dm}$ : TTC value

$\sum_{r=1}^{N_L} (P_{mn} + P_{nm}) = P_{loss}$ : Total real power loss of the transmission system

$PF$ : Penalty Function

$P_{Gm}$, $Q_{Gm}$: Active and reactive power generation at bus $m$

$P_{Dm}$, $Q_{Dm}$: Active and reactive power demand at bus $m$

$|V_m|\angle\delta_m$ : Complex voltage at bus $m$

$|Y_{mn}|\angle\theta_{mn}$ : $mn^{th}$ element of bus admittance matrix

$P_{Gm}^{\min}$, $P_{Gm}^{\max}$ : Active power generation limits at bus m

$Q_{Gm}^{\min}$, $Q_{Gm}^{\max}$ : Reactive power generation limits at bus m

$S_l^{\max}$ : Thermal limit of $l^{th}$ transmission line

$V_m^{\min}$, $V_m^{\max}$ : Voltage magnitude limits at bus m

$X_C^{\min} = -0.85 \times X_{mn}$ : Lower limit of reactance of TCSC

$X_C^{\max} = 0.2 \times X_{mn}$ : Upper limit of reactance of TCSC

$N_L$: Total number of transmission lines

$N_b$: Total number of buses

$N_G$: Total number of generator buses

Square penalty function is used to handle inequality constraints such as reactive power output of generator buses, voltage magnitude of all buses and transmission lines thermal limits as shown in (13) and (14).

$$PF = k_1 \times \sum_{m=1}^{N_G} f(Q_{Gm}) + k_2 \times \sum_{m=1}^{N} f(V_m) + k_3 \times \sum_{m=1}^{N_L} f(S_{lm}) \tag{13}$$

$$f(x) = \left\{\begin{array}{ll} 0 & if\ x^{\min} \le x \le x^{\max} \\ (x - x^{\max})^2 & if\ x > x^{\max} \\ (x^{\min} - x)^2 & if\ x < x^{\min} \end{array}\right\} \tag{14}$$

where,

$k_1$, $k_2$, $k_3$: Penalty coefficients for reactive output power of generator buses ($Q_{Gm}$), voltage magnitude ($V_m$) of all buses and transmission line loading ($S_{lm}$), respectively. They are the large positive constants in the range [$10^8$, $10^{10}$]. They will impose large penalty even on small violation of the limits of variables. Their higher values make penalty function steeper so the solution lies closer to the rigid limits.

$x^{\min}$, $x^{\max}$ : Minimum and maximum limits of variable $x$.

Also, constant power factor demands of consumers have been considered.

$$Q_{Dm} = \left(\frac{\sqrt{1 - (\cos\phi_m)^2}}{\cos\phi_m}\right) \times P_{Dm},\ m\forall LOAD\_SINK \tag{15}$$

where,

$Q_{Dm}$: Reactive power demand of load bus $m$ in sink area

$P_{Dm}$: Active power demand of load bus $m$ in sink area

$\cos\phi_m$: Power factor of load bus $m$ in sink area

## 4. MODELING OF BILATERAL AND MULTILATERAL TRANSACTIONS

A bilateral transaction is made directly between a seller and a buyer without any third party intervention. Mathematically, each bilateral transaction between a seller at bus *m* and buyer at bus *n* satisfies the following power balance relationship:

$$P_{Gm} - P_{Dn} = 0 \tag{16}$$

A multilateral transaction is a trade arranged by energy brokers and involves more than two parties. It may take place between a group of sellers and a group of buyers at different nodes. Mathematically, it satisfies the following power balance relationship:

$$\sum_{m \in SELLER} P_{Gm} - \sum_{n \in BUYER} P_{Dn} = 0 \tag{17}$$

where:

$P_{Gm}$ : Active power generation at bus m in a source area

$P_{Dn}$ : Active power demand at bus n in a sink area

*SELLER*: A group of seller buses which sell power to the buyers

*BUYER*: A group of buyer buses which buy power from the sellers.

Contingency analysis has been also carried out to study the impact of severe contingencies on the value of feasible TTC.

Mathematically, feasible TTC $= \underset{n}{Min}\left\{TTC_{IN}, TTC_{CON}^{n}\right\}$ (18)

where,

$TTC_{IN}$: Max. power transfer in system intact condition without considering any contingency

$TTC_{CON}^{n}$ : Max. power transfer under $n^{th}$ contingency.

## 5. PARTICLE SWARM OPTIMIZATION

PSO is a fast, simple and efficient population-based optimization method which was proposed by Eberhart and Kennedy. It has been motivated by the behavior of organisms such as fish schooling and bird flocking. In PSO, a "Swarm" consists of number of particles which represent the possible solutions. The coordinates of each particle is associated with two vectors, namely the position ($x_i$) and velocity ($v_i$) vectors. The size of both vectors is same as that of the problem space dimension. All particles in a swarm fly in the search space to explore optimal solutions. Each particle updates its position based upon its own best position, global best position among particles and its previous velocity vector according to the following equations:

$$v_i^{k+1} = w \times v_i^k + c_1 \times r_1 \times (p_{best_i} - x_i^k) + c_2 \times r_2 \times (g_{best} - x_i^k) \tag{19}$$

$$x_i^{k+1} = x_i^k + \chi \times v_i^{k+1} \tag{20}$$

where,

$v_i^{k+1}$ : The velocity of $i^{th}$ particle at $(k + 1)^{th}$ iteration

$w$ : Inertia weight of the particle

$v_i^k$ : The velocity of $i^{th}$ particle at $k^{th}$ iteration

$c_1$, $c_2$: Positive constants having values between [0, 2.5]

$r_1$, $r_2$: Randomly generated numbers between [0, 1]

$p_{best_i}$ : The best position of the $i^{th}$ particle obtained based upon its own experience

$g_{best}$: Global best position of the particle in the population

$x_i^{k+1}$ : The position of $i^{th}$ particle at $(k + 1)^{th}$ iteration

$x_i^k$ : The position of $i^{th}$ particle at $k^{th}$ iteration

$\chi$: Constriction factor. It may help in sure convergence. Its low value facilitates fast convergence and little exploration while high value results in slow convergence and much exploration.

If no restriction is imposed on the maximum velocity ($\nu_{max}$) of the particles then there is likelihood that particles may leave the search space. So velocity of each particle is controlled between ($-\nu_{max}$) to ($\nu_{max}$).

Suitable selection of inertia weight *w* provides good balance between global and local explorations. It is set according the following equation.

$$w = w_{max} - \frac{w_{max} - w_{min}}{iter_{max}} \times iter \tag{21}$$

Where, $w_{max}$ is the value of inertia weight at the beginning of iterations, $w_{min}$ is the value of inertia weight at the end of iterations, *iter* is the current iteration number and $iter_{max}$ is the maximum number of iterations.

## 6. ALGORITHM TO OPTIMALLY LOCATE TCSC FOR MAXIMIZING TTC AND MINIMIZING LOSSES USING PSO

(i) Input the data of lines, generators, buses and loads. Choose population size of particles and convergence criterion. Define type of power transaction.

(ii) Select reactance setting and location (line number) of TCSC as control variables.

(iii) Randomly generate population of particles with their variables in normalized form (i.e. between 0 and 1)

(iv) Randomly install one TCSC in a transmission line and check that TCSC is not employed on the same line more than once in each iteration. Find Denormalized value (actual value) of TCSC reactance and location of TCSC using following equation.

$X_{(Denormalized)} = X_{(min)} + (X_{max} - X_{min}) \times X_{(Normalized)}$. Where, $X_{min}$ and $X_{max}$ are minimum and maximum values of the variable. Denormalized value of location of TCSC is rounded to nearest integer. Modify the bus admittance matrix.

(v) Run full a.c. Newton-Raphson load flow to get line flows, active power generations, reactive power generations, line losses and voltage magnitude of all buses.

(vi) Calculate the penalty function of each particle using eqn. (13).

(vii) Calculate the fitness function of each particle using eqn. (6).

(viii) Find out the "global best" ($g_{best}$) particle having maximum value of fitness function in the population and "personal best" $(p_{best_i})$ of all particles.

(ix) Generate new population using eqns. (19) and (20).

(x) Go to step no. (iv) until maximum number of iterations are completed.

(xi) Fitness value of $g_{best}$ particle is the optimized (maximized) value of TTC and minimized value of losses. Coordinates of $g_{best}$ particle give optimal setting and location of TCSC respectively.

## 7. SIMULATION RESULTS AND DISCUSSIONS

The IEEE 30 bus and practical Uttar Pradesh State Electricity Board (UPSEB, INDIA) 75 bus systems have been used to demonstrate suitability of the proposed algorithm. The simulation studies were carried out on Pentium: IV, 512 MB of RAM, 1.8 $GH_Z$ system in MATLAB 7.1 platform.

### 7.1. IEEE 30 Bus System

The bus, line and generator data are taken from MATPOWER [19]. It consists of 6 generators and 41 transmission lines. The system is partitioned into three areas as shown in Fig. 2. Two transactions namely a bilateral transaction between a seller bus no. 2 in source area to buyer bus no. 21 in sink area and a multilateral transaction between area 3 (seller bus-3,4) to area 2 (buyer bus-12, 14, 15, 16, 17, 18, 19 and 20) with the three objective functions i.e. (i) simultaneously maximize TTC and minimize active power loss($P_{loss}$), (ii) maximize only TTC and (iii) minimize only active power loss, have been considered.

Table 1 shows the test results of bilateral transaction from bus 2 to bus 21.Optimized values of TTC, real power loss, TCSC setting and TCSC location are indicated in bold letters.

Case 1A shows the results of simultaneous maximization of TTC and minimization of active power loss. The base case load at bus 21 is 17.50 MW. TTC is 26.50 MW without installing TCSC, whereas after installing TCSC it is increased to 32.50 MW without violating system constraints. Active power loss is 3.60 MW without placing TCSC, but it is reduced to 3.58 MW after placing TCSC. Optimal location of TCSC is line no: 36, which is connected between bus 28 to bus 27 and optimal reactance of TCSC is -0.3360 p.u. Negative sign indicates that TCSC operates in capacitive mode. Limiting condition is the reactive power upper limit violation of generator G3, if further transaction takes place.

Case 1B shows the results of maximization of TTC only. TTC can be improved from 26.50 MW to 33 MW after placing TCSC. TCSC setting, location and limiting conditions are same as that of case 1A.

Case 1C shows the results of minimization of loss only. Base case TTC is 17.50 MW. $P_{loss}$ is 2.99 MW without placing TCSC, but it is reduced to 2.84 MW after placing TCSC. TCSC also has great influence in reducing reactive power loss ($Q_{loss}$). It reduces $Q_{loss}$ from 10.74 MVAR to 10.30MVAR.

Table 2 shows the test results of multilateral transaction from area 3 to area 2. The base case load at area 2 is 53 MW. As shown in case 2A, TTC value can be increased from 75.40 MW to 84.20 MW after placing TCSC. Optimal TCSC setting is -0.1136 p.u. and location is line 12-13. Lower voltage limit violation of bus no. 19 prevents further transaction.

In case 2B, TTC can be increased to 85.40 MW after placing TCSC in the line 12-13 with -0.099 p.u. setting. TTC of case 2B is higher than that of case 2A because case 2B only maximizes TTC, whereas case 2A optimizes composite objective function.

In Case 2C, $P_{loss}$ can be reduced from 2.34 MW to 2.17 MW after placing TCSC in the line 28-27 with -0.3361 p.u. setting. In addition, optimally place TCSC has significantly reduced reactive power losses in cases 2A, 2B and 2C.

Table 3 shows the test results of contingency analysis of multilateral transaction from area 3 to 2. Only the outage of largest generator G6 in area 2 and tripping of tie-line between bus 23-24 have been considered in the

**Table 1**

**Test Results of Bilateral Transaction from bus 2(area 1) to bus 21(area 3) of the IEEE 30 bus Test System**

| *Objective function* | | *Without TCSC* | *With TCSC* | *TCSC setting (p.u.)* | *Location of TCSC* | *Limit conditions* |
|---|---|---|---|---|---|---|
| Max. TTC & min. loss (Case 1A) | TTC (MW) | 26.50 | 32.50 | | | |
| | $P_{loss}$ (MW) | 3.60 | 3.58 | –0.3360 | Line 28 –27 | $Q_{G3}$ |
| | $Q_{loss}$ (MVAR) | 12.66 | 12.83 | | | |
| Max. only TTC (Case 1B) | TTC | 26.50 | 33.00 | | | |
| | $P_{loss}$ | 3.59 | 3.61 | –0.3361 | Line 28 –27 | $Q_{G3}$ |
| | $Q_{loss}$ | 12.66 | 12.93 | | | |
| Min. only loss (Case 1C) | TTC | 17.50 | 17.50 | | | |
| | $P_{loss}$ | 2.99 | 2.84 | –0.3360 | Line 28 –27 | $Q_{G3}$ |
| | $Q_{loss}$ | 10.74 | 10.30 | | | |

**Table 2**

**Test Results of Multilateral Transaction from area 3 to Area 2 of IEEE 30 Bus System**

| *Objective function* | | *Without TCSC* | *With TCSC* | *TCSC setting (p.u.)* | *Location of TCSC* | *Limit conditions* |
|---|---|---|---|---|---|---|
| Max. TTC & min. loss (Case 2A) | TTC(MW) | 75.40 | 84.20 | | | |
| | $P_{loss}$(MW) | 3.09 | 3.39 | –0.113 | Line 12-13 | $V_{19}$ |
| | $Q_{loss}$(MVAR) | 11.12 | 10.53 | | | |
| Max. only TTC (Case 2B) | TTC | 75.40 | 85.40 | | | |
| | $P_{loss}$ | 3.09 | 3.47 | –0.099 | Line 12-13 | $V_{19}$ |
| | $Q_{loss}$ | 11.12 | 11.03 | | | |
| Min. only loss (Case 2C) | TTC | 53.00 | 53.00 | | | |
| | $P_{loss}$ | 2.34 | 2.17 | –0.336 | Line 28-27 | $V_{19}$ |
| | $Q_{loss}$ | 8.71 | 8.15 | | | |

contingency analysis. The base case TTC (Case 3A) without TCSC is 75.40 MW. The outage of generator G6 (Case 3B) reduces contingency TTC without TCSC to 54.60 MW. So TTC value is decreased by 27.58% compared to that without contingency constraints. So it is revealed that contingency constraints significantly reduce the value of TTC. So market participants should submit their bids after considering contingency constraints.

In Case 3B, contingency TTC with TCSC is 61.80 MW which is 13.18% higher than contingency TTC without TCSC. So optimally placed TCSC can increase TTC under contingency condition also. Case 3B is the most severe contingency among Case 3B and Case 3C. So the feasible contingency TTC value with TCSC is 61.80 MW.

Test results indicate that optimally placed TCSC by PSO could significantly increase TTC, reduce real power

**Table 3**

**Test Results of Contingency Analysis of Multilateral Transaction from Area 3 to Area 2 of the IEEE 30 Bus Test System**

| *Case* | *TTC (MW) without TCSC* | *TTC (MW) with TCSC* | *TCSC setting (p.u.)* | *Location of TCSC* | *Limit conditions* |
|---|---|---|---|---|---|
| Normal (Case 3A) | 75.40 | 84.20 | -0.1136 | Line 12-13 | $V_{19}$ |
| Largest generator G6 outage in area 2 (Case 3B) | 54.60 | 61.80 | -0.2100 | Line 4-12 | Line 15-23 loading |
| Tie-line 23-24 outage (Case 3C) | 55.40 | 64.20 | -0.1136 | Line 12-13 | Line 15- 23 loading |
| Contingency TTC value | 54.60 | 61.80 | | ——— | |

losses and reactive power losses under normal and contingency conditions.

### 7.2. UPSEB 75 Bus System

The bus, line and generator data has been taken from [20]. It has 15 generators (at buses 1-15) and 98 transmission lines (including 24 transformer branches) as shown in Fig. 3. The system has been partitioned into five areas. TTC evaluation for different types of transactions between different areas have been studied, out of which test results of multilateral transaction from area 4 to area 5 and a few contingency cases have been discussed here.

Table 4 shows the test results of multilateral transaction from area 4 (seller bus-5, 6, and 7) to area 5 (buyer bus-28, 54, 56, 63, 65, and 73). Case 4A shows the results of simultaneous maximization of TTC and minimization of active power loss. The base case TTC is 1112.83 MW. The optimized value of TTC is 1130.83 MW without installing TCSC, whereas after installing TCSC it is increased to 1148.83 MW in a heavily loaded system. Optimal reactance of TCSC obtained using PSO is -0.0393 pu and optimal location is line 16-50. Limiting conditions which prevent further execution of transactions are the lower voltage limit violation at the bus 62, reactive power upper limit violation of generator G5 and apparent power limit violation of line 35-41. Case 4B shows the results of maximization of only TTC. TTC value can be improved from 1112.83 MW to 1130 MW without installing TCSC whereas it can be further improved to 1142.83 MW after placing TCSC. TCSC setting and location are same as that of Case 4A. Case 4C shows the results of minimization of only loss. After placing TCSC, the real power loss is reduced by 4.089% and reactive power loss is reduced by 3.25%. Optimal TCSC reactance is -0.0414 pu and location is line 38-39.

Table 5 shows the results of contingency analysis of multilateral transaction from area 4 to area 5. Only the outage of largest generator G15 and tripping of the most critical line 19-26 as suggested by [21] are considered in the contingency analysis. Feasible contingency TTC value is 1112.83 MW without placing TCSC and 1130.83 MW after placing TCSC.

**Table 4**
**Test Results of Multilateral Transaction from Area 4 to area 5 of UPSEB 75 Bus Test System**

| *Objective function* | | *Without TCSC* | *With TCSC* | *TCSC setting (p.u.)* | *Location of TCSC* | *Limit conditions* |
|---|---|---|---|---|---|---|
| Max. TTC & min. loss (Case 4A) | TTC (MW) | 1130.83 | 1148.83 | –0.0393 | Line 16-50 | $V_{62}$, $Q_{G5}$, Line 35-41 loading |
| | Ploss (MW) | 217.02 | 231.90 | | | |
| | Qloss (MVAR) | 2363.20 | 2358.64 | | | |
| Max. only TTC (Case 4B) | TTC | 1130 | 1142.83 | –0.0393 | Line 16-50 | $V_{62}$ Line 35-41 loading |
| | Ploss | 217 | 230.20 | | | |
| | Qloss | 2363.20 | 2344.60 | | | |
| Min. only loss (Case 4C) | TTC | 1112.83 | 1112.83 | –0.0414 | Line 38-39 | $V_{62}$ |
| | Ploss | 212.48 | 203.79 | | | |
| | Qloss | 2323.49 | 2247.77 | | | |

**Table 5**
**Test Results of Contingency Analysis of Multilateral Transaction from Area 4 to Area 5 of UPSEB 75 Bus Test System**

| *Case* | *TTC (MW) without TCSC* | *TTC(MW) with TCSC* | *TCSC setting (p.u.)* | *Location of TCSC* | *Limit conditions* |
|---|---|---|---|---|---|
| Normal (Case 5A) | 1130.83 | 1148.83 | -0.0393 | Line 16-50 | $V_{62}$,$Q_{G5}$, Line 35-41 loading |
| Largest generator G15 outage in sink area 5 (Case 5B) | 1112.83 | 1130.83 | -0.0821 | Line 28-55 | $V_{62}$,$Q_{G5}$, Lines 74-73, 41-42loading |
| Outage of Line 19-26 (Case 5C) | 1124.23 | 1136.83 | -0.0393 | Line 16-50 | $V_{62}$,$Q_{G5}$ |
| Contingency TTC value | 1112.83 | 1130.83 | | ——— | |

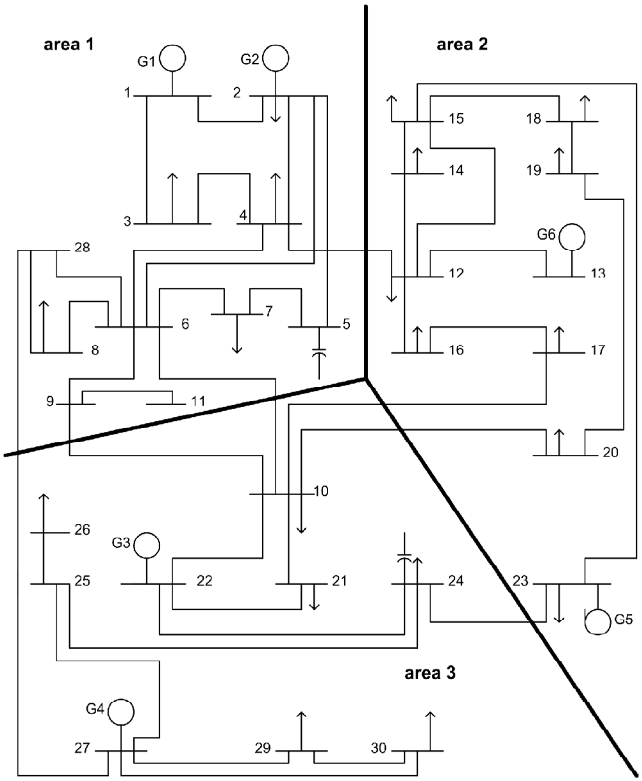


**Figure 2:** Single Line Diagram of IEEE 30 Bus Test System

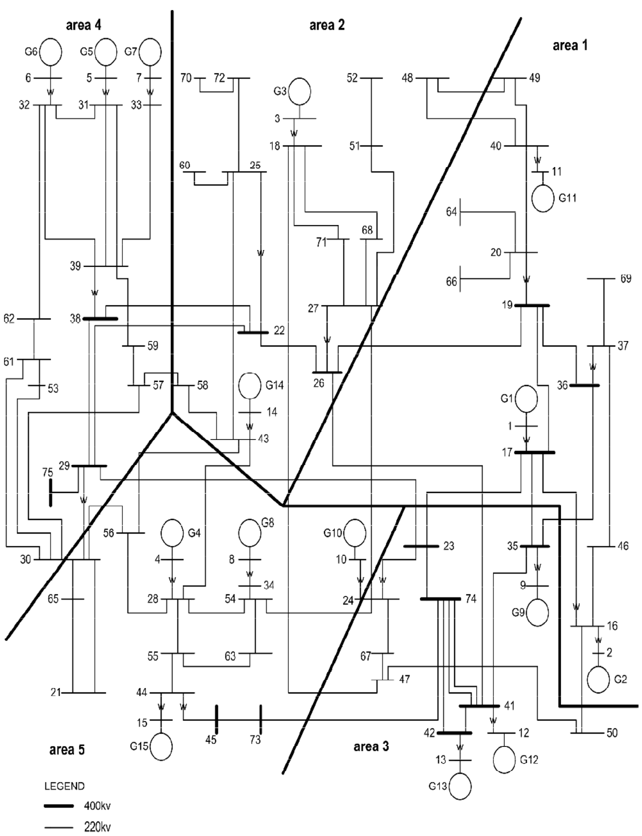


**Figure 3:** Single Line Diagram of UPSEB 75 Bus Test System

### 7.3. Effects of PSO Parameters on the Value of TTC

PSO parameters such as cognitive parameter ($C_1$), social parameter ($C_2$), Constriction factor ($\chi$), maximum inertia weight ($W_{max}$), minimum inertia weight ($W_{min}$), upper limit of velocity ($V_{max}$), and lower limit of velocity ($-V_{max}$) were selected through experiments for the both systems and their effects on the value of TTC have been studied. The results of IEEE 30 bus system are shown in Table 6. The population of 50 particles was taken for all cases 6A-6E and 20 independent trials were carried out for each case. It is observed that case 6B ($C_1$ = 1.4, $C_2$ = 1.4, $\chi$ = 1, $W_{max}$=0.93, $W_{min}$=0.4, $V_{max}$ = 0.0001, and $-V_{max}$ = –0.0001) gives the best TTC(84.20 MW) value. To check the convergence characteristics of PSO with the selected parameters of case 6B, simulations were carried out for 80 iterations. The variation in TTC with the iteration number is shown in Fig. 4. It can be observed that PSO converges in between 25 to 35 iterations for IEEE 30 bus system. In cases 6A, 6C, 6D and 6E, the particles have not explored the search space properly. So those cases exhibit premature convergence of PSO.

The population of 100 particles was selected for UPSEB 75 bus system and simulations were carried out for 80 iterations. The variation in TTC with the iteration number is given in Fig. 5. It can be observed that PSO converges in less than 40 iterations.

**Table 6**
**Effects of PSO Parameters on the Value of TTC of IEEE 30 Bus System**

| *Case* | *$C_1$, $C_2$* | *Constriction factor* | *$W_{max}$, $W_{min}$* | *$V_{max}$, $-V_{max}$* | *Average TTC (MW)* |
|---|---|---|---|---|---|
| 6A | 2,2 | 0.8 | 1.05, 0.5 | 0.0002, -0.0002 | 81.80 |
| 6B | 1.4,1.4 | 1 | 0.93, 0.4 | 0.0001, -0.0001 | 84.20 |
| 6C | 1,1.5 | 0.6 | 1,0.5 | 0.0030,-0.0030 | 81.80 |
| 6D | 1.5,2 | 0.5 | 0.8,0.4 | 0.040, -0.040 | 77 |
| 6E | 1.2, 1 | 0.3 | 0.7,0.3 | 0.25, -0.25 | 79.4 |

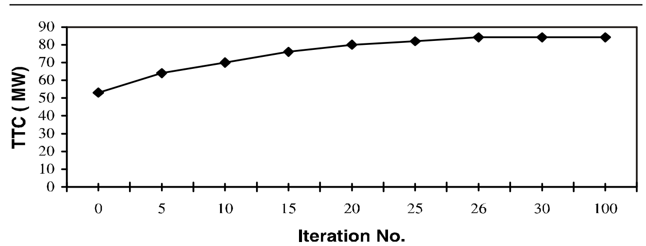


**Figure 4:** Convergence Characteristic of PSO for IEEE 30 Bus System

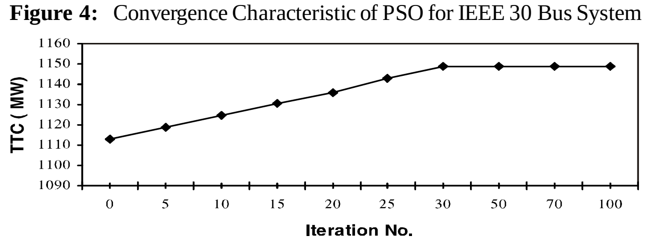


**Figure 5:** Convergence Characteristic of PSO for UPSEB 75 Bus System

## 8. CONCLUSIONS

This paper has proposed PSO based algorithm to find optimal location and setting of TCSC for maximizing TTC and minimizing total real power losses of the competitive electricity markets having bilateral and multilateral transactions. Simulations were performed on IEEE 30 bus system and practical UPSEB 75 bus system. Test results indicate that optimally placed TCSC by PSO could significantly increase TTC, reduce real power losses and reactive power losses under normal and contingency conditions. In addition, PSO exhibits robust convergence characteristic so it could be used to effectively calculate TTC.

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