Chapter 3

Optimal placement of Thyristor Controlled Series Compensator (TCSC) for Total Transfer Capability (TTC) enhancement

3.1 Introduction

Deregulation of the electricity markets throughout the world aiming in establishing competition between the various market players. It has created new technical challenges to market participants and power system researchers. So far as transmission systems are concerned, there should be sufficient TTC to fulfill scheduled transactions between the buyers and sellers and provide non-discriminaroty open access to market participants. Sufficient TTC should be guaranteed to support free market trading and maintain secure and economical operation over a wide range of system conditions. 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, tight restrictions on the construction of new facilities due to the increasingly difficult environmental, economic and social constraints, have proposed intensive shared use of the existing transmission lines by utilizing the Independent Power Producers (IPPs). This problem has motivated the development of new methods to enhance the TTC of the existing transmission systems. Consequently, power suppliers will get benefit from more market opportunities with less congestion and enhanced power system security. Also, it will be more profitable for transmission owners with optimized use of existing transmission assets; and consumers will get improved services at reduced prices.

To solve such problem, various TTC enhancement methods have been suggested so far, where rescheduling output power of generators, tap changing of on load tap changing transformer (OLTC), adjusting terminal voltage of generators are the obvious methods to enhance TTC [4]. It is also noticed that Flexible AC Transmission Systems (FACTS) may have great impact on the way the transmission system operates because of its power flow control capability and rapid action. From the perspective of steady-state power flow, circuits under normal conditions do not share power in proportion to their ratings, and thus in most of the cases, voltage profile does not remain smooth. As a result, TTC values are always limited by heavily loaded lines and busbars with relatively low voltage profile, with the increase of system loading. By controlling line reactance, TCSC enables line loading to increase flexibly, and some cases upto thermal limits. So, TCSC offers an effective and promising alternative to conventional methods for TTC enhancement. To resolve problems of deregulated electrical power systems in 1990s, the Electric Power Research Institute (EPRI) had proposed that besides flexible power flow control over designated routes, another major application of a TCSC is to increase the power transfer capability of transmission systems [22].

So, as mentioned above, the main point of the restructured power system is the ability of accurately and rapidly quantifying the capabilities of the transmission systems. TTC is limited by a number of different mechanisms like thermal, voltage and stability constraints. So, utilities would have to determine the adequacy their Available Transfer Capabilities (ATCs) to ensure that the system reliability has been maintained. Also, large increase in power demand, competition among various market players and scare natural resources are some factors due to which transmission systems operate very near to their thermal and stability limits. But, because of economic, environmental and political reasons it is not practical and preferable to build new transmission lines. So there is an interest in better utilization of existing capacities of power systems by installing FACTS device like TCSC. It is the power electronics based componenet which can enhance TTC, voltage stability, loadability, security etc. and can reduce active and reactive power losses, cost of generation, remove congestion and fulfill transaction requirement rapidly, dynamically and efficiently.

Because of the following reasons, it is necessary to "optimally" locate TCSC in order to obtain its full benefits, as

(1) It is a costly device;

(2) It may have adverse effect on system stability unless it is optimally placed[61];

(3) It may reduce profit of some market participants in deregulated power system [97];

Hence, this chapter presents various terms related to TTC definitions and various concepts for dealing the technical challanges of computation. Also, Particle Swarm Optimization based algorithm has been suggested to find optimal locaiton and setting of TCSC for simultaneously maximizing the Total Transfer Capability and minimizing total real power losses of the competitive electricity markets consisting of bilateral and multilateral transactions. The performance of the proposed algorithm has been tested on IEEE 30 bus test system and practical Uttar Pradesh State Electricity Board (UPSEB, INDIA) 75 bus test systems.

3.2 TTC definitions and related terms

There has been a great interest in quantifying the transmission capabilities of power system since many years. When size of the systems was small, these capabilities were easy to determine and consisted only thermal ratings and voltage drop limitations. But, for large interconnected power systems, these concepts do not remain valid. So, 1996 document of NERC has introduced several new terms, which have been redefined the concepts of the 1995 documents and specifically identify quantities associated with the uncertainty in the modeling and system conditions [9].

3.2.1 Available Transfer Capability (ATC)

It is measure of the transfer capability remaining in the physical transmission network for further commercial activity over and above already committed uses. It can be expressed as:

$$ATC = TTC - TRM - (\sum ETC + CBM) \tag{3.1}$$

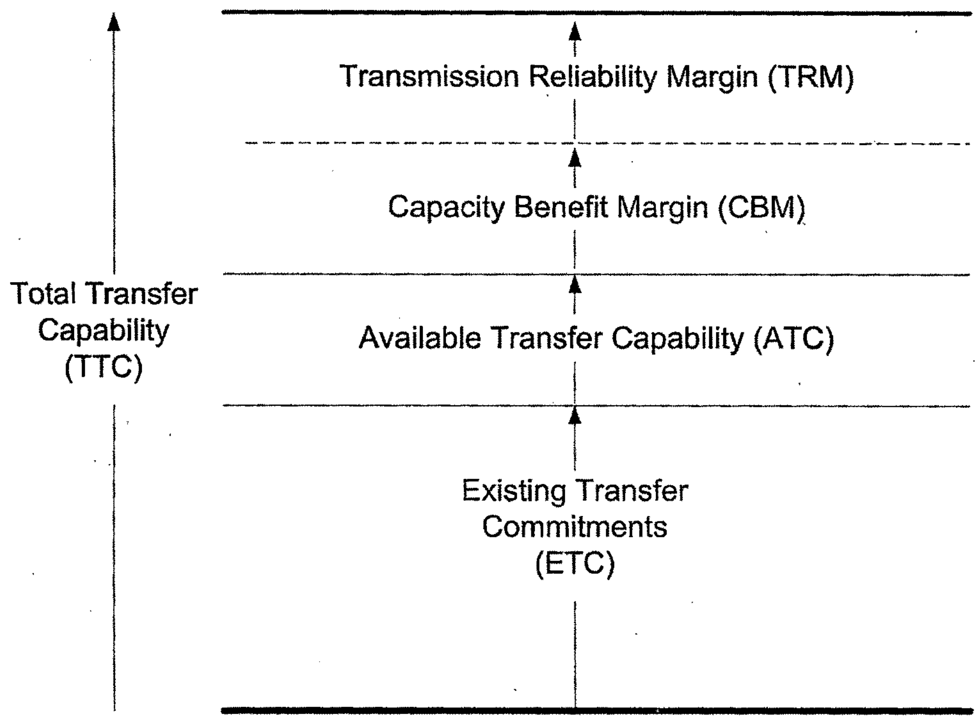

Figure 3.1: Basic definition of TTC

3.2.2 Total Transfer Capability (TTC)

It is defined as the amount of electric power that can be transferred over the interconnected transmission network in a reliable manner while meeting all of a specific set of defined pre and post contingency system conditions. TTC value may reflect contractual arrangements or be based on certain equipment limitations or system conditions. TTC represents the reliability limit of a transmission path at any specified point in time.

ATC/TTC calculations are made and posted on Open Access Same Time Information System (OASIS) for three time horizons as described herein:

3.2.2.1 Scheduling Horizon (Real-time):

OASIS calculates the ATC/TTC after the operating horizon closes, typically at 3:00 PM pacific time the day before transactions are scheduled to occur. In addition, OASIS recalculates ATC/TTC continuously during the operating and scheduling horizons as new TSR are confirmed and as soon as schedules are received and approved for existing reservations. TTC is also recalculated whenever new e-tags are received and impact either firm or non firm TTC.

Firm ATC is defined as: Firm ATC=TTC-(TRM+CBM+Existing transmission commitments(ETC)+firm reservations)

Non Firm ATC is defined as: Non Firm ATC=TTC-(Confirmed firm schedules+Confirmed non firm reservations+Firm counter schedules)

3.2.2.2 Operating horizon (Pre-schedule/Day ahead)

OASIS calculates ATC as e-Tags are approved throughout the Pre-schedule day and runs to the end of the Pre-schedule day(s) per the Western Electricity Coordinating Council (WECC) Pre-schedule Calendar. PacifiCorp's OASIS re-calculates ATC continuously during the Operating and Scheduling Horizons as new TSRs are confirmed and as soon as schedules are received and approved for existing reservations.

Operating Horizon Formulas: (1) Firm ATC = TTC - (TRM + CBM + ETC + Firm Reservations) (2) Non-Firm ATC = TTC – (TRM + CBM + Confirmed Firm Schedules [e-Tags] + Confirmed Non-Firm Reservations) + Firm Counter Schedules [e-Tags]

3.2.2.3 Planning horizon

Firm ATC is calculated using the long range load forecasts filed by Network Transmission Customers annually with their Load and Resource (L&R) submittals. L&R submittals are consistent with integrated resource plans filed with the 3 regional regulatory entities (State Utility Commissions). Existing Transmission Commitments (ETC), TRM, CBM, and confirmed Long-Term Firm Point-to-Point Transmission Service Requests (including rollover assumptions) are utilized to calculate firm ATC in the Planning Horizon. Non-firm ATC is calculated and posted by deducting any confirmed Short-Term Non-Firm Point-to-Point Transmission Service Requests.

Planning Horizon Formulas: (3) Firm ATC = TTC - (TRM + CBM + ETC + Firm Reservations) (4) Non-Firm ATC = TTC – (TRM + CBM + ETC + Firm Reservations + Non-Firm Reservations)

3.2.3 Transmission Reliability Margin (TRM)

It is defined as the amount of transfer capability necessary to provide a reasonable level of assurance that the interconnected transmission network will be secured. TRM accounts for the inherent uncertainty in system conditions, its associated effects on ATC calculation, and the need for operating flexibility to ensure reliable system operation as system conditions change. It considers the uncertainty in operating conditions such as those in model parameters(e.g line impedance) or load forecasting errors. Some of the components that should be considered in calculating TRM are: (1) aggregate load forecasting error, (2) load distribution error, (3) variations in facility loadings for balancing load and generation within a control area, (4) uncertainties in forecasting the system topology, (5) allowances for parallel path impacts, (6) allowances for simultaneous path interactions, (7) variations in generation dispatch due to component outages, and (8) variations in short-term operator response/operating reserves. The calculated values of these terms may change based on the human experience and means of forecasting the system conditions.

3.2.4 Existing Transmission Commitments (ETC)

The measure of any transmission capacity committed for use. Existing Transmission Commitments (ETCs) are a Transmission Provider's existing transmission capacity obligations which may include grandfathered transmission contracts, OATT transmission reservations, Native Load usage, reasonably forecasted (over the Planning Horizon) Native or Network Load growth, or other obligations that impact Firm ATC.

3.2.5 Capacity Benefit Margin (CBM)

It is defined as the amount of firm transfer capability preserved for load serving entities on the host transmission system where their load is located, to enable the access to generation from interconnected systems to meet generation reliability requirements [16]. Preservation of CBM for a LSE allows that entity to reduce its installed generating capacity below what may otherwise have been necessary without interconnections to meet its generation reliability requirements. The transmission capacity preserved as CBM is intended to be used by LSE only in times of emergency generation deficiencies.

3.2.6 Curtailability

It is defined as the right of a transmission provider to interrupt all or part of a transmission service due to constraints that reduce the capability of the transmission network to provide that transmission service. Transmission service is to be curtailed only in cases where system reliability is threatened or emergency conditions exist.

3.2.7 Recallability

It refers to whether or not a service is recallable. It is a transmission provider's right to interrupt all or part of transmission service for any reason, including the economics, that is consistent with the FERC policy and the TP's transmission service tariffs or contract provisions. Non-recallable ATC is defined as TTC less TRM, less non-recallable reserved transmission service (including CBM). Recallable ATC is defined as TTC less TRM, less recallable transmission service, less non-recallable transmission service (including CBM).

Fig. 3.1 shows TTC/ATC and their related terms. They form the basis of transmission service reservation system that will be used to reserve and schedule transmission services in the new competitive electricity markets. As the competitive electricity markets become mature, more will be learned on how these markets will operate and how the definitions of TTC may be changed and used.

3.3 Calculation of total transfer capability and some technical challenges

The calculation of total transfer capability is generally based on computer simulations of the operation of interconnected transmission network under a specific set of assumed operating conditions. Each simulation represents a single "snapshot" of the operation of the interconnected network based on the projections of many factors. As such, they are viewed as reasonable indicators of network performance and available transfer capability.

The interconnected network is dynamic in nature. Therefore, the transfer capability of the network will also vary with respect to time. For this reason, transfer capability calculations may need periodic updates for operation of the network. In addition, depending on actual network conditions, transfer capabilities can often be higher or lower than those determined in the off-line studies. Important factors which may be considered in the simulations are:

3.3.1 Voltage limits

System voltages and changes in voltages must be maintained within the range of acceptable minimum and maximum limits.

$$V_{min} \leq V_i \leq V_{imax} \tag{3.2}$$

Where,

V_{min}: Minimum acceptable value of system voltage

V_{max}: Maximum acceptable value of system voltage

3.3.2 Stability limits

The transmission network must be capable of surviving disturbances through the transient and dynamic time-periods (from milliseconds to several minutes, respectively) following the disturbances. All generators connected to the AC interconnected transmission systems operate in synchronism with each other at the same frequency. Immediately following a system disturbance, generators begin to oscillate relative to each other, causing fluctuations in system frequency, line loadings and system voltages. For the system to be stable, the oscillations must diminish as the electric systems attain a new, stable operating point.

Therefore, the transfer capability of the transmission network may be limited by the physical and electrical characteristics of the systems including thermal, voltage, and stability consideration. A significant number of generation and transmission system contingencies should be screened, consistent with individual electric system, power pool, sub regional, and regional planning criteria, to ensure that the facility outage most restrictive to the transfer being studied is identified and analyzed. Somtimes, multiple contingencies may be evaluated. Once the critical contingencies are identified, their impact on the network must be evaluated to determine the most restrictive of those limitations. Therefore, the total transfer capability becomes:

$$TTC = lesser\,of\,\{Thermal\,limit,\ Voltage\,limit,\ Stability\,limit\}\,following\,N-1^{contingency} \tag{3.3}$$

3.3.3 Parallel path flows

When electric power is transferred across the network, parallel path flow occurs proportional to the relative impedance of the parallel paths. This complex electric transmission network phenomenon can affect all systems of an interconnected network, especially those systems electrically near the transacting systems. As a result, transfer capability determination must be sufficient in scope to ensure that limits throughout the interconnected network are addressed. In some cases, the parallel path flows may result in transmission limitations in systems other than the transacting systems, which can limit the transfer capability between the two contracting areas.

3.3.4 Maintaining voltage levels

Maintain appropriate voltage levels, based on operational procedures, on critical buses for the studied base-cases. If a bus voltage is outside the tolerance band, the Regional Transmission Engineer (RTE) utilizes the voltage control devices including, synchronous condensers, shunt capacitors, shunt reactors, series capacitors, generators, etc.

3.3.5 Projected customer demand

Base case demand levels should be appropriate to the system conditions and customer demand levels under study and may be representative of peak, off-peak and light demand conditions.

3.3.6 Contingency analysis

3.3.6.1 General

After the RTE has updated one or more base-cases, the next step in determining transfer capability for local area procedures is for the RTE to perform contingency analysis studies in an effort to determine the limiting conditions for the outage.

Pre-contingency load flow analysis involves modeling pre-contingency steady state conditions and measuring the respective line flows, bus voltages, etc.

Post-contingency load flow analysis involves modeling post-contingency conditions and measuring the respective line flows, bus voltages, etc.

3.3.6.2 Operating criteria and study standards

To perform contingency analysis in a consistent manner, the RTE adheres to the standards below. These standards are derived from North American Electric Reliability Council (NERC) reliability standards [10], and historical operating experience.

Pre-contingency operating criteria:

All pre-contingency line flows shall be at or below their normal ratings. All pre-contingency bus voltages shall be within a pre-determined operating range.

Post-contingency operating criteria:

All post-contingency line flows shall be at or below their emergency ratings. All post-contingency bus voltages shall be within a pre-determined operating range.

Contingency analysis:

The RTE models the contingencies when performing contingency analysis, including:

Generator outages (G-1), Line outages (L-1), Line outage combined with one generator outage (L-1+G-1), Transformer outages (T-1), Synchronous condenser outages, Shunt capacitor outages, Series capacitor outages, Static VAR compensator outages.

Bus outages:

Bus outages can be considered for the following ongoing outage conditions. For a circuit breaker bypass and clear outage, bus contingencies shall be taken on both bus segments that the bypasses circuit breaker connects to. For a bus segment outage, the remaining parallel bus segment shall be considered as a single contingency.

The concepts for determining total transfer capability described in NERC's transmission transfer capability reference document are still valid and has not been changed with the advent of open transmission access. Each region, sub-region, power pool, and individual system will have to consider the TTC principles given in NERC documentation and determine the best procedure for calculating TTCs based upon their respective circumstances. Following criteria must be taken into account while evaluating TTC in static and dynamic modes

Static TTC:

Generator active and reactive power limits, Voltage limits, Line flow limit.

Dynamic TTC:

Generator active and reactive power limits, Voltage limits, Line flow limit and angular stability limit.

3.4 Static modeling of Thyristor Controlled Series Compensator (TCSC)

As shown in Fig.3.2 the TCSC has been represented by a variable capacitive/inductive reactance inserted in series with the transmission line. So the reactance of the transmission line is adjusted by TCSC directly.

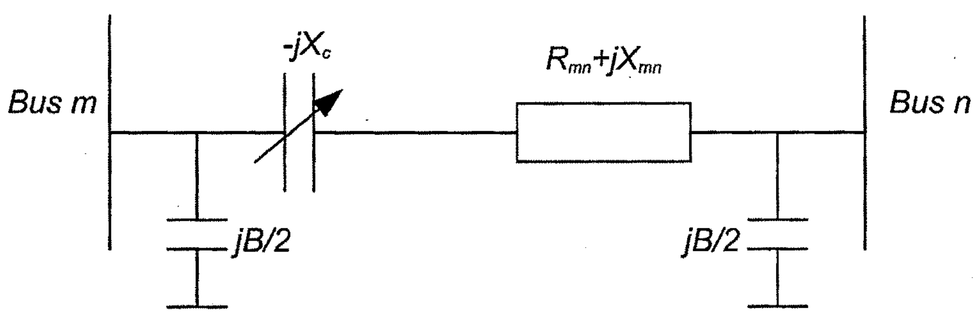

Figure 3.2: Equivalent circuit of a transmission line after placing TCSC

Let, X_{mn} is the reactance of the transmission line, X_c 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 follows:

$$X_{new} = X_{mn} - X_c \tag{3.4}$$

The modified power flow equations of the transmission due to insertion of TCSC can be written as follows:

$$P_{mn} = V_m^2 G_{mn} - V_m V_n (G_{mn} cos\delta_{mn} + B_{mn} sin\delta_{mn}) \tag{3.5}$$

$$Q_{mn} = -V_m^2 (B_{mn} + B/2) + V_m V_n (G_{mn} sin\delta_{mn} - B_{mn} cos\delta_{mn}) \tag{3.6}$$

$$P_{nm} = V_n^2 G_{nm} - V_m V_n (G_{nm} cos\delta_{nm} - B_{nm} sin\delta_{nm}) \tag{3.7}$$

$$Q_{nm} = -V_n^2 (B_{nm} + B/2) + V_m V_n (G_{nm} sin\delta_{nm} + B_{nm} cos\delta_{nm}) \tag{3.8}$$

Where,

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

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

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

G_{mn}: Resultant conductance of the line after placing TCSC

B_{mn}: Resultant susceptance of the line after placing TCSC

R_{mn}: Resistance of the line

If TCSC is connected between bus m and bus n, then only following entries of bus admittance matrix (y_{bus}) will change. i.e. mm, mn, nm and nn entries will change. Let us consider a simple example. Suppose system consists of 5 buses and TCSC is connected between bus 2 and bus 3. If TCSC offers a change in net line admittance by $\triangle y$, the admittance matrix will become as follows:

$$\begin{matrix} y_{11} & y_{12} & y_{13} & y_{14} & y_{15} \\ y_{21} & (y_{22}+\Delta y) & (y_{23}-\Delta y) & y_{24} & y_{25} \\ y_{31} & (y_{32}-\Delta y) & (y_{33}+\Delta y) & y_{34} & y_{35} \\ y_{41} & y_{42} & y_{43} & y_{44} & y_{45} \\ y_{51} & y_{52} & y_{53} & y_{54} & y_{55} \end{matrix} \tag{3.9}$$

3.5 Proposed PSO based algorithm to optimally locate TCSC for maximizing TTC and minimizing losses

The basic idea behind the TTC calculation is to determine for a given set of the system conditions (generation dispatch, load level, network configuration and line flow limits), the maximum amount of power that a transmission system can transport, in addition to the already committed transmission services, when power is injected at one location(seller bus) and the same amount of power is extracted at the same time at another location (buyer bus) without any violation of transmission constraints. The additional amount of power is referred as the TTC between the two locations in the network. Enhancement of TTC is very important issue in the current open market. Heavily loaded lines and buses with relatively low voltages, usually limit the TTC. As TCSC can change the reactance of the transmission line very rapidly and efficiently, it is an important FACTS device which can be used to enhance TTC and reduce the losses. But as mentioned earlier, because of the following reasons, it is necessary to "optimally" locate TCSC in order to obtain its full benefits, as

(1) It is a costly device;

(2) It may have adverse effect on system stability unless it is optimally placed[61];

(3) It may reduce profit of some market participants in deregulated power system[97];

So, Particle Swarm Optimization based algorithm has been suggested to find optimal locaiton and setting of TCSC for simultaneously maximizing the Total Transfer Capability and minimizing total real power losses of the competitive electricity markets consisting of bilateral and multilateral transactions. The performance of the proposed algorithm has been tested on IEEE 30 bus test system and practical Uttar Pradesh State Electricity Board (UPSEB, INDIA) 75 bus test systems.

3.5.1 Optimal power flow model

A multi-objective optimal power flow to optimally locate TCSC for maximizing TTC and minimizing total real power loss, subject to satisfy various equality and inequality constraints is given as follows:

$$Max \left\{ w_1 * \left(\sum_{m=1}^{LOAD_{sink}} P_{Dm} \right) - w_2 * \left(\sum_{r=(m,n),r\in N_L}^{N_L} (P_{mn} + P_{nm}) \right) - PF \right\} \tag{3.10}$$

The OPF is subjected to various equality constraints (power flow balance equations)

$$\left\{ P_{Gm} - P_{Dm} - \sum_{n=1}^{N_b} |V_m||V_n||Y_{mn}|cos(\delta_m - \delta_n - \theta_{mn}) = 0 \right\}, For\ each\ PV\ bus\ except\ slack\ bus \tag{3.11}$$

$$\left\{ Q_{Gm} - Q_{Dm} - \sum_{n=1}^{N_b} |V_m||V_n||Y_{mn}|sin(\delta_m - \delta_n - \theta_{mn}) = 0 \right\},\ For\ each\ PQ\ bus \tag{3.12}$$

Various inequality constraints (operating constraints)

$$P_{Gm}^{min} \leq P_{Gm} \leq P_{Gm}^{max},\ m \in N_G \tag{3.13}$$

$$Q_{Gm}^{min} \leq Q_{Gm} \leq Q_{Gm}^{max},\ m \in N_G \tag{3.14}$$

$$|S_l| \leq S_l^{max},\ l \in N_L \tag{3.15}$$

$$V_m^{min} \leq V_m \leq V_m^{max},\ m \in N_b \tag{3.16}$$

$$X_c^{min} \leq X_c \leq X_c^{max}\ pu \tag{3.17}$$

Where,

w_1 and w_2: Weighting coefficients in the range [0,1] which indicate the relative importance of the conflicting objectives. In the present work, w_1 and w_2 are taken as 0.5. So, both objectives are given same importance. Also, $w_1 + w_2 = 1$.

$LOAD_{sink}$: Total number of load buses in sink area

PF: Penalty Function

$$\sum_{m=1}^{LOAD_{sink}} PD_m \text{ : Total Transfer Capability} \tag{3.18}$$

Total real power loss of the transmission system is expressed as follows:

$$\sum_{r=1}^{N_L}(P_{mn} + P_{nm}) = P_{loss} \text{ : Total real power losses of the transmission system} \tag{3.19}$$

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}: Minimum and maximum active power generation limits of generator G connceted at bus m respectively

Q_{Gm}^{min}, Q_{Gm}^{max}: Minimum and maximum reactive power generation limits of generator G connceted at bus m respectively

S_l^{max}: Apparent power limit of l^{th}transmission line

V_m^{min}, V_m^{max}: Minimum and maximum voltage magnitude limits at bus m respectively

X_c^{min}= -0.85*X_{mn}: Lower limit of reactance of TCSC

X_c^{max}= 0.2*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 line thermal limits as shown below.

$$PF = \left\{ k_1 * \sum_{m=1}^{N_G} f(Q_{Gm}) + k_2 * \sum_{m=1}^{N} f(V_m) + k_3 * \sum_{m=1}^{N_L} f(S_{lm}) \right\} \tag{3.20}$$

$$f(x) = \begin{cases} 0,\ if\ x^{min} \leq x \leq x^{max} \\ (x - x^{max})^2, if\ x > x^{max} \\ (x^{min} - x)^2, if\ x < x^{min} \end{cases} \tag{3.21}$$

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 of [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.

$$Q_{Dm} = \frac{\sqrt{1-(cos\phi_m)^2}}{cos\phi_m} * P_{Dm},\ m \in LOAD_{sink} \tag{3.22}$$

Where,

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

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

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

3.5.2 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

$$P_{Gm} - P_{Dn} = 0 \tag{3.23}$$

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

$$\sum_{m \in SELLER} P_{Gm} - \sum_{n \in BUYER} P_{Dn} = 0 \tag{3.24}$$

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.

3.5.3 Contingency analysis

Contingency analysis has been also carried out to study the impact of severe contingencies on the value of feasible TTC. Mathematically it is expressed as:

$$Feasible\,TTC = Min_n\{TTC_{IN}, TTC^n_{CON}\} \tag{3.25}$$

Where:

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

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

3.5.4 Step by step algorithm to optimally locate TCSC for maximizing TTC and minimizing losses using PSO

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

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

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

4. 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

$$X_{(Denormalized)} = X_{(min)} + (X_{max} - X_{min}) * X_{(Normalized)} \tag{3.26}$$

   Where, $X_{min}$and X_{max} are minimum and maximum values of the variable X respectively. Denormalized value of location of TCSC is rounded to nearest integer during optimization. Modify the bus admittance matrix.

5. Run Newton-Raphson load flow to get line flows, active power generations, reactive power generations, line losses and voltage magnitude of all buses.

6. Calculate the penalty function of each particle using equ. 3.20

7. Calculate the fitness function of each particle equ. 3.10

8. Find out the "global best" particle having maximum value of fitness function in the population and "personal best" of all particles.

9. Update the velocity and position of each particle using equs. 2.1 and 2.2

10. Go to step no. (4) until maximum number of iterations are completed.

11. 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 a TCSC, respectively.

3.6 Results and Discussions

To establish the effectiveness of the proposed method, the simulation studies were conducted on the following two sample test systems.

1. IEEE 30-bus test system as described in Appendix B

2. A practical 75-bus UP state electricity board (UPSEB) system representing 220KV and 400KV network as described in Appendix C.

In this chapter, Particle Swarm Optimization based algorithm has been suggested to find optimal locaiton and setting of TCSC for simultaneously maximizing the Total Transfer Capability (TTC) and minimizing total real power losses of the competitive electricity markets consisting of bilateral and multilateral transactions.

3.6.1 IEEE 30-bus test system

The bus, line and generator data taken from [3] consists of 6 generators and 41 transmission lines. The system is partitioned into three areas as shown in Appendix B and Fig. B.1.

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. (1) Simultaneously maximize TTC and minimize active power loss(P_{loss}), (2) Maximize only TTC and (3) Minimize only active power loss, have been considered.

Table 3.1 shows the test results of bilateral transaction from bus 2 to bus 21. 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. Ploss 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 3.1: Test results of bilateral transaction from bus 2 (area 1) to bus 21 (area 3) of the IEEE 30-bus test system

Objective functions		Without TCSC	With TCSC	TCSC setting (pu)	Location of TCSC	Limit condition
Max. TTC & Min. losses (Case 1A)	TTC (MW)	26.50	32.50	-0.3360	Line 28-27	Q_{G3}
	P_{loss}(MW)	3.60	3.58			
	Q_{loss}(MVAR)	12.66	12.83			
Max. only TTC (Case 1B)	TTC (MW)	26.50	33.00	-0.3361	Line 28-27	Q_{G3}
	P_{loss}(MW)	3.59	3.61			
	Q_{loss}(MVAR)	12.66	12.93			
Min. only losses (Case 1C)	TTC (MW)	17.50	17.50	-0.3360	Line 28-27	Q_{G3}
	P_{loss}(MW)	2.99	2.84			
	Q_{loss}(MVAR)	10.74	10.30			

Table 3.2 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, Ploss 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 placed TCSC has significantly reduced reactive power losses in cases 2A, 2B and 2C.

Table 3.2: Test results of multilateral transaction from area 3 to area 2 of IEEE 30-bus test system

Objective functions		Without TCSC	With TCSC	TCSC setting (pu)	Location of TCSC	Limit condition
Max. TTC & Min. losses (Case 2A)	TTC (MW)	75.40	84.20	-0.113	Line 12-13	V_{19}
	P_{loss}(MW)	3.09	3.39			
	Q_{loss}(MVAR)	11.12	10.53			
Max. only TTC (Case 2B)	TTC (MW)	75.40	85.40	-0.099	Line 12-13	V_{19}
	P_{loss}(MW)	3.09	3.47			
	Q_{loss}(MVAR)	11.12	11.03			
Min. only losses (Case 2C)	TTC (MW)	53.00	53.00	-0.3360	Line 28-27	V_{19}
	P_{loss}(MW)	2.34	2.17			
	Q_{loss}(MVAR)	8.71	8.15			

Table 3.3 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 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.

Table 3.3: Test results of contingency analysis of multilateral transaction from area 3 to area 2 of IEEE 30-bus test system

Test case	TTC(MW) without TCSC	TTC(MW) with TCSC	TCSC setting(pu)	Location of TCSC	Limit conditions
Normal (Case 3A)	75.40	84.20	-0.1136	Line between buses (12-13)	V_{19}
Largest generator G_6outage in area 2 (Case 3B)	54.60	61.80	-0.2100	Line between buses (4-12)	Line between buses (15-23) loading
Tie line 23-24 outage (Case 3C)	55.40	64.20	-0.1136	Line between buses (12-13)	Line between buses (15-23) loading
Contingency TTC value	54.60	61.80			

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.

3.6.2 UPSEB 75-bus test system

The bus, line and generator data have been taken from [7]. It consists of 15 generators (at buses 1-15) and 98 transmission lines (including 24 transformer branches) as shown in Appendix C and Fig. C.1. 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 are discussed here.

Table 3.4 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 3.4: 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 (pu)	Location of TCSC	Limit conditions
Max. TTC & Min. losses (Case 4A)	TTC (MW)	1130.83	1148.83	-0.0393	Line between buses (16-50)	V_{62}, Q_{G5}, line between buses (35-41) loading
	P_{loss}(MW)	217.02	231.90			
	Q_{loss}(MVAR)	2363.20	2358.64			
Max. only TTC (Case 4B)	TTC (MW)	1130	1142.83	-0.0393	Line between buses (16-50)	V_{62}, line between buses (35-41) loading
	P_{loss}(MW)	217	230.20			
	Q_{loss}(MVAR)	2363.20	2344.60			
Min. only loss (Case 4C)	TTC (MW)	1112.83	1112.83	-0.0414	Line between buses (38-39)	V_{62}
	P_{loss}(MW)	212.48	203.79			
	Q_{loss}(MVAR)	2323.49	2247.77			

Table 3.5 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) [100] have been considered in the contingency analysis. Feasible contingency TTC value is 1112.83 MW without placing TCSC and 1130.83 MW after placing TCSC.

Table 3.5: 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 (pu)	Location of TCSC	Limit conditions
Normal (Case 5A)	1130.83	1148.83	- 0.0393	Line between buses (16-50)	V_{62}, Q_{G5}, line between buses (35-41) loading
Largest generator G_{15}outage in sink area 5 (Case 5B)	1112.83	1130.83	- 0.0821	Line between buses (28-55)	V_{62}, Q_{G5}, line between buses (74-73) and (41-42) loading
Outage of line between buses (19-26) (Case 5C)	1124.23	1136.83	- 0.0393	Line between buses (16-50)	V_{62}, Q_{G5}
Contingency TTC value	1112.83	1130.83	—	—	—

3.6.3 Effect of PSO parameters on the value of TTC

The various parameters of PSO greatly affect its convergence. So, PSO parameters such as cognitive parameter (C_1), social parameter (C_2), Constriction factor (χ), maximum inertia weight (W_{max}), minimum inertia weight (W_{min}), upper limit of velocity (V_{max}), and lower limit of velocity (V_{min}) 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 3.6. The population of 50 particles was taken for all cases 6A-6E and 20 independent trials were carried out for each case. It was observed that case 6B (C_1=1.4, C_2=1.4,χ =1, W_{max}=0.93, W_{min}=0.4, V_{max}= 0.0001, and Vmin =0.0001) gave 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 100 iterations. The variation in TTC with the iteration number is shown in Fig. 3.3 It could be observed that PSO converged 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 exhibited premature convergence of PSO.

Table 3.6: Effect of PSO parameters on the value of TTC in IEEE 30-bus test system

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

The population of 100 particles was selected for UPSEB 75-bus system and simulations were carried out for 100 iterations. The variation in TTC with the iteration number is given in Fig. 3.4 It was observed that PSO converged in less than 40 iterations. So, this study shows that PSO is a fast method, which can easily obtain optimal or sub-optimal solution.

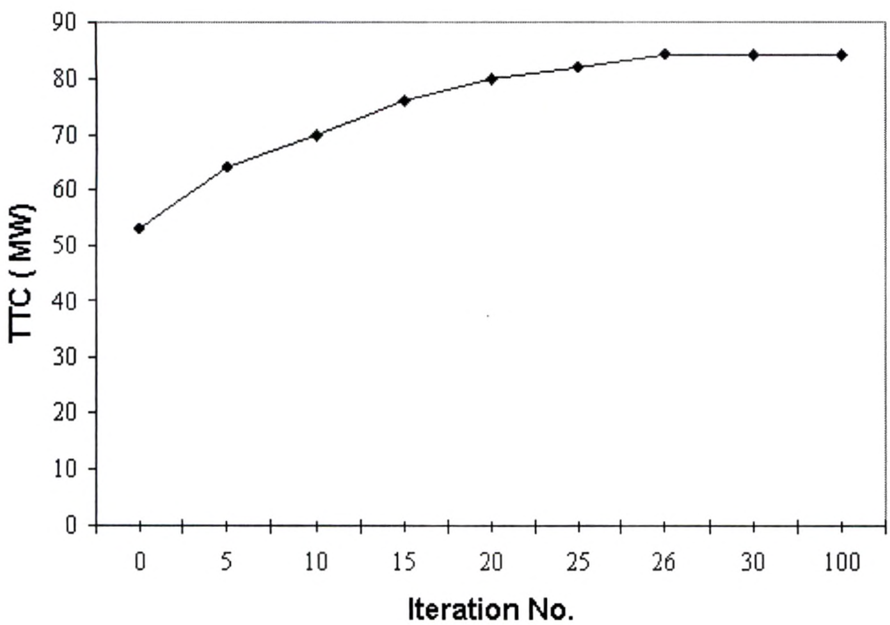

Figure 3.3: Convergence characteristic of PSO in IEEE 30-bus test system

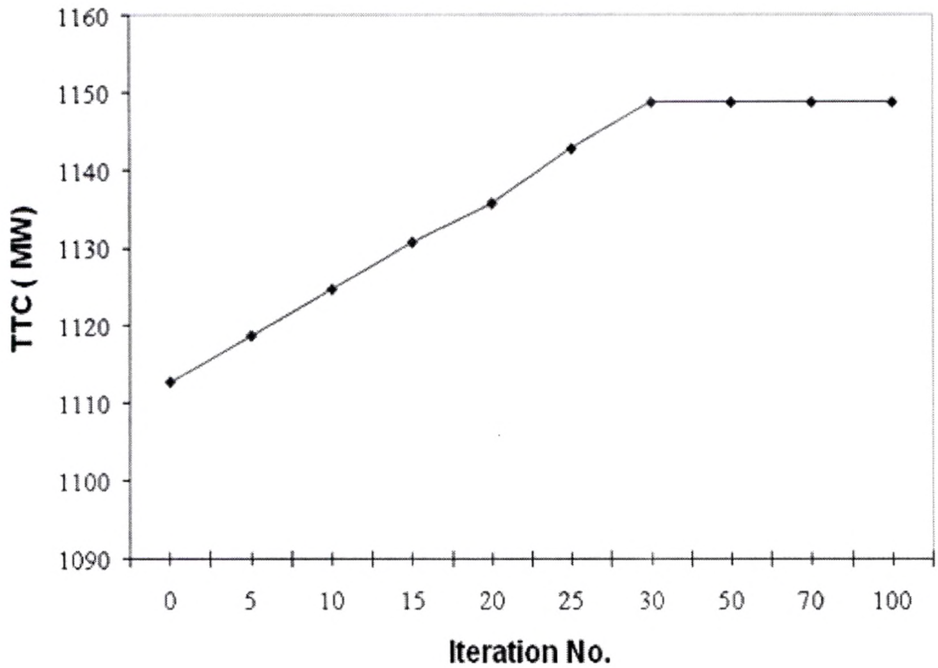

Figure 3.4: Convergence characteristic of PSO in UPSEB 75-bus test system

3.7 Conclusions

To facilitate the deregulated electricity market operation, control and trading, sufficient transmission capability should be provided to satisfy increasing demand of power transactions reliably. The conflict of this requirement and the restrictions on the transmission expansion in the deregulated electricity market has motivated the development of methodology to enhance the TTC of the existing transmission grid. The contribution of this chapter can be summarized as follows:

1. This work 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 which consist of bilateral and multilateral transactions.

2. 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.

3. PSO exhibits robust convergence characteristic so it could be used to effectively calculate TTC.

4. PSO obtains global solution within 40 iterations, so the proposed method can be used to evaluate TTC in on-line TTC measurement system.