Chapter 5

Impact of optimally placed TCSC on transmission pricing, wheeling charges and bilateral transactions

5.1 Introduction

A one of the major features of the deregulated electrical power system is to charge all customers on a non-discriminatory basis for transmission services. Derivation of charges for the different kinds of transmission services should be simple, transparent and stable. Correct pricing of transmission services is useful in providing economic signals for efficient short-run operations, recovery of costs, long-term capital investments and fair allocation of costs among the all participants [5]. Increased number of market participants, non-discriminatory nature of independent system operator and suitable real and reactive pricing are necessary conditions for a ideal competition in an open power market. Increase in market participation can be created using proper pricing mechanism so that market participants can invest in future plan for future need [38].

Since TRANSCO has a monopolistic characteristic, transmission open access means a tool for promoting necessary competition in generation side. So, establishment of rules for operating the transmission network (a technical matter) and for pricing transmission services (an economic matter) is the real challenging task. This task is highly complex as it involves technical, economical, political and legal aspects [26]. Transmission pricing should fulfill following goals:

1. Recover costs of transmission network and its operation,

2. Provide assured open access (equitable treatment and opportunity) for all users,

3. Encourage investment in transmission and efficiency of use,

4. Provide a simple and understandable price structure and

5. It should be implementable in the real system.

The electric utility industries are undergoing rapid changes due to their restructuring and deregulation. The rapidly increasing cost of electricity in recent years has brought about awareness to the importance of pricing policies in maximizing social welfare. Electric energy is treated as a commodity which can be bought, sold and transmitted taking into account its time-varying values and costs, known as "spot pricing". In the deregulated market, all utility-consumer transactions are based on a single quantity , the hourly spot price. Schweppe et al [2] were among the first to discuss the spot price of electricity. They presented a novel concept of spot pricing which was shown to encompass and achieve more fully the objectives of rate structures and load management techniques. Their spot pricing theory extends traditional economic dispatch theory. In spot pricing theory, the objective function maximizes system benefit; equivalent to minimizing system cost, subject to the constraints of generator limit, limits on power flow of transmission lines and other constraints of FACTS device. The major difference between spot pricing and traditional economic dispatch lies in the number of Lagrange multiplier revealing the system marginal cost of electricity, the spot pricing approach calculates marginal cost of electricity at each bus of the network and for each point in time, thus the name, "Spot pricing".

Since last many years, there has been a lot of discussion regarding the implementation of a spot market for electricity. Such market would give consumers price signals allowing them to adjust and modify their loads in order to get the most out of their consumption of electricity. Spot pricing helps in defining wheeling rates i.e. the price, wheeling utility charges (normally TRANSCO) for use of its transmission network. Most of the recent works deal with the issue of spot pricing using OPF, having objective as production cost minimization. Both, the production cost function (GENCOs' bid functions) and consumer demand function (DISCOs' bid functions) are taken simultaneously in the objective function to give the optimal real time price of real and reactive powers at generators buses and load buses. Though, it is an established fact that the flow of reactive power affects both the transmission losses and voltage magnitudes, very little attention has been given to the pricing of reactive power. The creation of full spot market without reactive power pricing may not be satisfactory.

Very less papers have been published so far, which have considered the impact of "Optimally" placed TCSC on the magnitude of spot prices, wheeling charges and bilateral transactions simultaneously. Verma et al.[94] used sensitivity based and sequential quadratic programming approach to study the impact of UPFC on real and reactive power spot prices. Archarya et al.[97] used sequential quadratic programming to study impact of TCSC on congestion and spot price. But it did not optimize TCSC setting and location. Singh et al.[100] proposed reactive power spot price index to optimally place SVC to minimize total generation cost and to maximize loading margin. Sharma et al.[125] used mixed integer nonlinear programming to locate UPFC to optimize secure bilateral transaction matrix for pool and bilateral electricity markets.

So, in this chapter the impact of "Optimally" placed TCSC on the magnitude of spot prices, wheeling charges and bilateral transactions have been studied out. Firstly, cost minimization OPF has been solved by PSO to find the optimal values of control variables like generators' active power output, bus voltage of generators, TCSC setting and TCSC location. Generators' cost functions and consumers' bid functions are considered separately. Secondly, out of many suggested pricing methods, Locational Marginal Pricing (LMP or Spot Price) method is popular because it considers all system constraints and losses. As PSO can not provide Lagrange multipliers which are required for finding LMP, an interior point method is used to calculate LMP. But choice of initial starting points [37] greatly affect the quality of solution of an interior point method. So in this chapter, optimized outputs obtained from PSO method are used as starting points of interior point method and results are compared with those obtained by using default starting points of Primal Dual Interior Point Method used in MATPOWER [105]. MATPOWER is a power system simulation package in which optimal power flow can be solved by using various classical optimization methods. Lastly, influence of optimally placed TCSC by PSO on wheeling charges and secure bilateral transaction matrix has been studied and results have been compared with those obtained by Primal Dual Interior Point Method. IEEE 6-bus test system, IEEE 30-bus test system and UPSEB 75-bus test systems have been used to study the effectiveness of the proposed algorithm.

5.2 OPF formulation and swarm initialization in PSO

The major steps involved in the OPF formulation are given below:

5.2.1 Initialization of a population

A particle consists of continuous and integer control variables. The continuous variables include the generators' active power outputs (PG_2,..... PG_{NG}), generators' bus voltages (VG_1,.....VG_{NG}) and reactance (X_c) value of TCSC. Generators' active powers and generators's bus voltages are generated randomly within their permissible minimum and maximum limits. Reactance of TCSC is generated randomly between 0 and 1 (normalized form, $X_{(N)}$) and its actual value ($X_{(D)}$,Denormalized value) is found using equ. 5.1

$$X_{(D)} = X_{(min)} + (X_{max} - X_{min}) \times X_{(N)} \tag{5.1}$$

Where,

X_{min} and X_{max} are minimum and maximum values of the variable.

The integer variable consists of possible location (Loc) of a TCSC between the two buses. The particles are generated in matrix from as shown in table 5.1.

5.2.2 Installation of a TCSC

First generate initial population of particles for control parameters. For each particle, TCSC is randomly installed in the transmission line with randomly generated reactance. Then

Table 5.1: Representation of a particle

Particle No.	Continuous control variables							Integer control variables
	PG_2	...	PG_{NG}	VG_1	...	VG_{NG}	X_c	Location
1	$PG_{2,1}$	...	$PG_{NG,1}$	$VG_{1,1}$	...	$VG_{NG,1}$	X_{c1}	Loc_1
2	$PG_{2,2}$	...	$PG_{NG,2}$	$VG_{1,2}$	...	$VG_{NG,2}$	X_{c2}	Loc_2
...	...	...	...	...	...	...	...	...
i	$PG_{2,i}$	...	$PG_{NG,i}$	$VG_{1,i}$	...	$VG_{NG,i}$	X_{ci}	Loc_i

Where,

$\mathbf{PG}_{2,i}, \mathbf{PG}_{NG,i}$: From $\mathbf{2^{nd}}$ **to** $\mathbf{NG^{th}}$ generators' active output powers corresponding to i^{th} particle excluding slack bus generator power.

As slack generator takes care of losses during the load flow computation, its output power has not been considered as a control variable. Slack bus is assigned number 1. So, $\mathbf{PG}_1$is not considered as a control variable.

$\mathbf{VG}_{1,i}, \mathbf{VG}_{NG,i}$: From $\mathbf{1^{st}}$ **to** $\mathbf{NG^{th}}$generators' voltage magnitudes corresponding to the i^{th} particle including slack bus generator voltage.

Slack bus voltage is generally specified as input variable during load flow analysis, so it is considered as a control variable during optimization.

$\mathbf{X}_{ci}$: Reactance of a TCSC corresponding to i^{th} particle.

$\mathbf{Loc}_i$: Location (line number) of a TCSC corresponding to i^{th} particle.

If TCSC is not included in the transmission system, then variables $\mathbf{X_c}$ and $\mathbf{Loc}_i$are not considered.

If there are total i number of particles and if each particle consists of j number of control variables, then the dimension of a population becomes $i \times j$

after, location and value of TCSC reactance have been determined. Finally, new value of bus admittance matrix is found out.

5.2.3 Power flow

Run Newton-Raphson power flow to obtain generators' active and reactive output powers, bus voltages, load angles, line flows, active and reactive power losses of transmission lines.

5.2.4 Optimal power flow problem formulation

An OPF (fitness function) to minimize total generation cost considering installation cost of TCSC subject to various equality and inequality constraints using PSO can be formulated as equ. 5.2.

$$Min \left\{ \sum_{m=1}^{N_G} C_{Gm}(P_{Gm}) - \sum_{n=1}^{N_D} B_{Dn}(P_{Dn}) + (IC_{TCSC}) + (PF) \right\} \tag{5.2}$$

An OPF for maximizing social welfare without considering TCSC can be formulated as equ. 5.3.

$$Min \left\{ \sum_{m=1}^{N_G} C_{Gm}(P_{Gm}) - \sum_{n=1}^{N_D} B_{Dn}(P_{Dn}) + (PF) \right\} \tag{5.3}$$

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

$$\left\{ P_{Gm} - P_{Dm} - \sum_{n=1}^{N_b} |V_m||V_n||Y_{mn}|cos(\delta_m - \delta_n - \theta_{mn}) = 0 \right\}, For\ each\ \ PV\ bus\ except\ \ slack\ bus \tag{5.4}$$

$$\left\{ Q_{Gm} - Q_{Dm} - \sum_{n=1}^{N_b} |V_m||V_n||Y_{mn}|sin(\delta_m - \delta_n - \theta_{mn}) = 0 \right\},\ For\ each\ PQ\ bus \tag{5.5}$$

Various inequality constraints (operating constraints)

$$P_{Gm}^{min} \leq P_{Gm} \leq P_{Gm}^{max},\ m \in N_G \tag{5.6}$$

$$Q_{Gm}^{min} \leq Q_{Gm} \leq Q_{Gm}^{max},\ m \in N_G \tag{5.7}$$

$$|S_l| \leq S_l^{max},\ l \in N_L \tag{5.8}$$

$$V_m^{min} \leq V_m \leq V_m^{max},\ m \in N_b \tag{5.9}$$

$$X_c^{min} \leq X_c \leq X_c^{max}\ pu \tag{5.10}$$

Where,

$C_{Gm}(P_{Gm})$: Bid function of m^{th}generator bus (seller bus)

$B_{Dn}(P_{Dn})$: Bid function of n^{th}consumer bus (buyer bus)

IC_{TCSC}: Optimal Installation cost of TCSC (US$)

PF: Penalty function

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

$P_{Dm},\ Q_{Dm}$: Active and reactive power generation 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 connected at bus m respectively

$Q_{Gm}^{min},\ Q_{Gm}^{max}$: Minimum and maximum reactive power generation limits of generator G connected 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$\times X_{mn}$: 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

N_D: Total number of load buses

The cost function of TCSC is given in Siemens database and used in Cai et al [65]. Mathematically it is written as equ. 5.11.

$$C_{TCSC} = 0.0015(S)^2 - 0.7130(S) + 153.75 \, (US\$/KVAR) \tag{5.11}$$

Where, C_{TCSC} is the cost of TCSC in US$/KVAR and S is the operating range of the TCSC in MVAR.

$$S = |Q_1| - |Q_2| \, (MVAR) \tag{5.12}$$

Where, Q_1 is the reactive power flow in the line before placing TCSC in MVAR and Q_2 is the reactive power flow in the line after placing TCSC in MVAR.

The installation cost (US$) of TCSC is given by equ. 5.13.

$$IC_{TCSC} = C_{TCSC} \times S \times 1000 \tag{5.13}$$

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 in equs. 5.14 and 5.15.

$$PF = k_1 \times \sum_{m=1}^{N_G} f(Q_{Gm}) + k_2 \times \sum_{m=1}^{N} f(V_m) + k_3 \times \sum_{m=1}^{N_L} f(S_{lm}) \tag{5.14}$$

$$f(x) = \begin{cases} 0, \; if \; x^{min} \le x \le x^{max} \\ (x - x^{max})^2, if \; x > x^{max} \\ (x^{min} - x)^2, if \; x < x^{min} \end{cases} \tag{5.15}$$

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. The value of each coefficient is equal to 1000.

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

5.3 Active and Reactive power spot prices for generators

Suppose, Generator's cost function (bid function) is given by the equ. 5.16

$$C^s_{g(b)}(P_{g(b)}) = \alpha^s_{g(b)} P^2_{g(b)} + \beta^s_{g(b)} P_{g(b)}, \; for \; g(b) = 1, ..., n \tag{5.16}$$

Where,

$C^s_{g(b)}(P_{g(b)})$(\$/h) is the cost of generator $g(b)$ at bus b for generating P amount of power at its supply level s,

$P_{g(b)}$(MW) is the amount of active power generated by generator $g(b)$,

$\alpha^s_{g(b)}$ (\$/MW^{2}h) is the predetermined cost coefficient in the generator cost function,

$\beta^s_{g(b)}$(\$/MWh) is another cost coefficient in the generator cost function.

n is the total number of generators in the network.

The locational marginal price (LMP or spot price) is the cost of supplying next MW of load at a specific location, considering generation marginal cost, cost of transmission congestion and losses [148]. According to [114], the active power spot prices (LMP) of generators can be found by solving the first order conditions of their cost functions and apply the "optimal" values of $P_{g(b)}$ obtained by PSO as follows:

Active power spot price for each generator $g(b)$ is given by equ.5.17.

$$2\alpha^{s}_{g(b)}P_{g(b)} + \beta^{s}_{g(b)},\ for\ g(b) = 1, ..., n \tag{5.17}$$

Suppose, Generator's reactive power cost function (bid function) is given by the equ. 5.18.

$$C^{s'}_{g(b)}(Q_{g(b)}) = \alpha^{s'}_{g(b)}Q^2_{g(b)} + \beta^{s'}_{g(b)}Q_{g(b)},\ for\ g(b) = 1, ..., n \tag{5.18}$$

Where,

$C^{s'}_{g(b)}(Q_{g(b)})$(\$/h) is the cost of generator $g(b)$ at bus b for generating Q amount of reactive power at its supply level s',

$Q_{g(b)}$(MVAR) is the amount of reactive power generated by generator $g(b)$,

$\alpha^{s'}_{g(b)}$ (\$/MVAR^{2}h) is the predetermined cost coefficient in the generator cost function,

$\beta^{s'}_{g(b)}$(\$/MVARh) is another cost coefficient in the generator cost function.

The reactive power spot price is the cost of supplying next MVAR of load at a specific location, considering generation marginal cost, cost of transmission congestion and losses [148]. According to [114], the reactive power spot prices (LMP) of generators can be found by solving the first order conditions of their cost functions and apply the "optimal" values of $Q_{g(b)}$ obtained by PSO as follows:

Reactive power spot price for each generator $g(b)$ is given by equ. 5.19.

$$2\alpha^{s'}_{g(b)}Q_{g(b)} + \beta^{s'}_{g(b)},\ for\ g(b) = 1, ..., n \tag{5.19}$$

5.4 Active and Reactive power spot prices for consumers

Suppose, consumer's utility function (bid function) is given by the equ. 5.20

$$U^{d}_{l(b)}(L_{l(b)}) = -\gamma^{d}_{l(b)}L^{2}_{l(b)} + \delta^{d}_{l(b)}L_{l(b)},\ for\ l(b) = 1, ..., m \tag{5.20}$$

Where,

$U^{d}_{l(b)}(L_{l(b)})$($/h) is the utility of load $l(b)$ at bus b for consuming L amount of active power at its demand level d,

$L_{l(b)}$(MW) is used to represent the amount of active power consumed by customers $l(b)$,

$-\gamma^{d}_{l(b)}$ ($/MW^{2}h) is the predetermined cost coefficient in the consumer utility function,

$\delta^{d}_{l(b)}$($/MWh) is another cost coefficient in the consumer utility function,

m is the total number of loads (customer groups).

The locational marginal price (LMP or spot price) is the cost of supplying next MW of load at a specific location, considering generation marginal cost, cost of transmission congestion and losses [148]. According to [114], the active power spot prices (LMP) of consumers can be found by solving the first order conditions of their utility functions and apply the "optimal" values of $L_{l(b)}$obtained by PSO as follows:

Active power spot price for each consumer $l(b)$ is given by equ. 5.21.

$$-2\gamma^{d}_{l(b)}L_{l(b)} + \delta^{d}_{l(b)},\ for\ l(b) = 1, ..., m \tag{5.21}$$

Suppose, consumer's reactive power bid function is given by the equ. 5.22.

$$U^{d'}_{l(b)}(Q_{l(b)}) = -\gamma^{d'}_{l(b)}Q^{2}_{l(b)} + \delta^{d'}_{l(b)}Q_{l(b)},\ for\ l(b) = 1, ..., m \tag{5.22}$$

Where,

$U^{d'}_{l(b)}(Q_{l(b)})$($/h) is the utility of load $l(b)$ at bus b for consuming Q amount of reactive power at its demand level d,

$Q_{l(b)}$(MVAR) is used to represent the amount of reactive power consumed by customers $l(b)$,

$-\gamma^d_{l(b)}$ (\$/MVAR^{2}h) is the predetermined cost coefficient in the consumer utility function,

$\delta^d_{l(b)}$(\$/MVARh) is another cost coefficient in the consumer utility function,

m is the total number of loads (customer groups).

The reactive power spot price is the cost of supplying next MVAR of load at a specific location, considering generation marginal cost, cost of transmission congestion and losses [148]. According to [114], the reactive power spot prices (LMP) of consumers can be found by solving the first order conditions of their utility functions and apply the "optimal" values of $Q_{g(b)}$ obtained by PSO as follows:

Reactive power spot price for each consumer bus $l(b)$ is given by equ. 5.23.

$$-2\gamma^{d'}_{l(b)}Q_{l(b)} + \delta^{d'}_{l(b)}, for\ l(b) = 1, ..., m \tag{5.23}$$

5.5 Basic concept of wheeling charges

Wheeling is the transaction of electric power from a seller to a buyer bus through a transmission network owned by one or more parties. Wheeling rates are payments made by the buyers or the sellers (or both) to the wheeling utility to compensate it for the generation and network costs incurred.

The wheeling can be broadly classified in four categories as follows:

1. Bulk power wheeling that involves transaction of two fully regulated utilities using network of a third utility.

2. Customer wheeling in which an independent customer purchases power from an utility using network of another party.

3. Supplier wheeling in which an independent GENCO sells power to an utility using network of another party.

4. Supplier to customer wheeling in which an independent GENCO sells power to an independent customer using a network of a third party.

Pricing of transmission services plays a crucial role in determining whether the service provided is economically beneficial to both the wheeling utility and the wheeling consumers. The network utility provides the condition for the pricing of its service in a competitive fashion, responding in real time to the prevailing supply and demand conditions. There are two critical elements in this definition : prices are determined in real time and are determined by market-based competition. In the traditional monopolistic market, the knowledge of costs is used to minimize total cost of generation. But as the electricity market moves towards open competition, setting of transmission prices become more and more difficult. The following are the popular pricing schemes which are employed for the transmission services [21].

5.5.1 Embedded cost based pricing:

This method is based on recovering, on pro data basis, the embedded capital cost, average annual operating cost, replacement cost considering service life and depreciation.

5.5.2 Incremental cost based pricing:

This method employes economic load dispatch formulation to compute Short Run Marginal Cost (SRMC) or Long Run Marginal Cost (LRMC). In case of SRMC, revenue reconciliation is required to recover the capital cost.

5.5.3 Combination of above two methods:

Some of the methods based on embedded cost methodology and incremental cost calculations have been given as follows:

5.5.4 Flat Fee method:

In this method, transmission changes are equally distributed amongst all the customers irrespective of their use of the network. This is the simplest method of pricing. Yet, the charges become unfair to those customers who consume lesser amount of electricity.

5.5.5 Postage Stamp method:

In this method, transmission prices are charged equally on per MW basis of transaction, irrespective of distance (similar to the postage stamp). It may be calculated different for different time of a day. In this scheme, a customer drawing same amount of power as another one but located farther from the source point is charged same transmission price, whereas its use of transmission network is more.

5.5.6 MW-Mile method:

The pricing in this method also considers the distance involved in a transaction apart from the amount of power being transacted. The distance may be aerial or circuit length. Charges may vary on different times of a day. Some of the controversies to be addressed by this method are the actual 'displacement of power' and 'parallel flows'.

5.5.7 Contract path method:

This method is similar to the MW-Mile method except that the transmission of power between two points are charged based on the rate of a fixed contracted path. Even though this method is simple, if offers a bad implementation of true transmission pricing, as power flows cannot be restricted to predefined path in case parallel paths are available.

5.5.8 Rated system path method:

This method overcomes the limitations of the contract path method. This method employes power flow simulation to determine the flow of a transacted power in various lines. The transacting parties are required to pay to all the lines based on the %ge of the capacity being used.

5.5.9 Location Based Marginal (LBM) costing:

This method employes OPF formulation for SRMC and LRMC calculations and determines cost of additional MW at a node. Marginal cost based wheeling charge is the cost of wheeling the scheduled real and reactive power, and is the difference of (the sum of the marginal rate based costs of real and reactive power at all consumer buses) and (the sum of marginal rate based costs of real and reactive power at all source buses).

5.6 Computation of wheeling rates

Wheeling is the transmission of electrical energy from a seller bus to a buyer bus through a transmission network owned by a third party. wheeling rates are the charges given to the transmission owner. These wheeling rates are based on marginal costs adjusted up or down as necessary to account for embedded capital costs. An ideal system of wheeling rates should satisfy a number of criteria such as:

1. Cause buying and selling utilities to make efficient wheeling decisions based on operating costs, embedded capital cost and power system security.
2. Enable multiple wheeling transactions to occur simultaneously.
3. Provide incentives to utilities strengthen their transmission system when mutually beneficial to all utilities.
4. Allow for as much decentralized decision-making as possible while providing a range of consistent options that match transaction costs with benefits.
5. Reduce as much as possible the opportunity for arbitrary or political decisions on wheeling rates.
6. Be feasible to calculate and implement.

Wheeling rate (W_p) for the real power can be expressed as equ. 5.24.

$$W_p = \lambda_{pB} - \lambda_{pS} \tag{5.24}$$

Where, $\lambda_{pB}$is the spot price of real power at the buyer bus-B,

λ_{pS} is the spot price of real power at the seller bus-S,

Wheeling charge for purchase of real power (P_B) is expressed as equ. 5.25.

$$WC_p = P_B \times W_p \tag{5.25}$$

Wheeling rate (W_q) for the reactive power can be expressed as equ. 5.26.

$$W_q = \lambda_{qB} - \lambda_{qS} \tag{5.26}$$

Where, $\lambda_{qB}$is the spot price of reactive power at the buyer bus-B,

λ_{qS} is the spot price of reactive power at the seller bus-S,

Wheeling charge for purchase of reactive power (Q_B) is expressed as equ. 5.27.

$$WC_q = Q_B \times W_q \tag{5.27}$$

Total wheeling charges are expressed as equ. 5.28.

$$W = WC_p + WC_q \tag{5.28}$$

5.7 Basics of bilateral transaction

A transaction is a bilateral exchange of power between generators and customers acting as seller and buyer buses and can be firm and non-firm. These bilateral transactions can affect the loading of transmission facilities and that may require system operator (SO) to reschedule the system generating units in order to accommodate them. A bilateral transaction is deemed to be feasible if it can be accommodated without any violation of system operating constraints such as transmission interface limits, equipments ratings, and system economic dispatch etc. A bilateral transaction is deemed to be infeasible if it violates any of system operating constraints. Infeasible bilateral transactions cannot be allowed as it may cause congestion, can threaten system security, reliability and alter economic dispatch schedule.

Thus, it has become important to determine the secure bilateral transactions in an open access environment before these can be negotiated between buying and selling entities [146].

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:

$$P_{Gm} - P_{Dn} = 0 \tag{5.29}$$

where,

P_{Gm} is the active power generation at bus m,

P_{Dn} is the active power demand at bus n.

The secure bilateral transaction matrix is obtained from the proposed bilateral transaction matrix after obtaining social benefit.

Let,

T_{mn} is the secured bilateral transaction between seller and buyer buses.

T^o_{mn} is the proposed bilateral transaction between seller and buyer buses.

$$Min \sum_m \sum_n (T_{mn} - T^o_{mn})^2 \tag{5.30}$$

The value of secure bilateral transaction matrix has been obtained with and without optimally placed TCSC using PSO. Its value is also obtained by interior point method and results obtained by PSO method is compared with those obtained from interior point method.

5.8 Results and Discussions

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

1. IEEE 6-bus test system as described in Appendix A

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

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

In this chapter the impact of "Optimally" placed TCSC on the magnitude of spot prices, wheeling charges and bilateral transactions have been studied out. Firstly, cost minimization OPF has been solved by PSO to find the optimal values of control variables like generators' active power output, generators' bus voltages, TCSC setting and TCSC location. Generators' cost functions and consumers' bid functions are considered separately. Secondly, out of many suggested pricing methods, Locational Marginal Pricing (LMP or Spot Price) method is popular because it considers all system constraints and losses. As PSO can not provide Lagrange multipliers which are required for finding LMP, an interior point method is used to calculate LMP. But choice of initial starting points [37] greatly affect the quality of solution of an interior point method. So in this chapter, optimized outputs obtained from PSO method are used as starting points of interior point method and results have been compared with those obtained by using default starting points of Primal Dual Interior Point Method using MATPOWER [105]. Lastly, influence of optimally placed TCSC by PSO on wheeling charges and secure bilateral transaction matrix has been studied and results have been compared with those obtained by Primal Dual Interior Point Method. IEEE 6-bus test system, IEEE 30-bus test system and UPSEB 75-bus test systems have been used to study the effectiveness of the proposed algorithm. The results of the three systems are described below.

5.8.1 IEEE 6-bus test system

The data of 6 bus system [105] consists of 3 generators and 11 transmission lines. In Table 5.2, Real power spot prices and Reactive power spot prices (Locational Marginal Price) of all generator buses and load buses are given. The spot prices of real power are very high as compared to that of reactive power. Most of the active power spot prices obtained at load buses by PSO method (Case A) are lower than that of interior point method (Case E). So it is cleared that consumers' surplus increase when PSO's optimized outputs are used as starting point for interior point method. Similarly, most of the active power spot prices obtained at generator buses by PSO method (Case A) are higher than that of interior point method (Case E). So producers' surplus increase when PSO's optimized results are used as starting point for IP method. Same results are obtained for reactive power spot price. Comparing Cases B and F, it is observed that PSO based solutions give better results than Interior Point method. Optimally placed TCSC reduces real power spot price (Case C) and reactive power spot price (Case D) of all load buses and some generator buses. It is because TCSC redistributes power flow in the transmission lines in such a way to decrease the losses and thus it tries to equalize spot prices at various load buses. Thus, TCSC increases consumers' surplus and producers' surplus.

Table 5.2: Comparison of LMPs obtained by PSO and interior point methods

Bus no.	Optimized solutions of PSO used as starting points in PDIPM (without TCSC)		Optimized solutions of PSO used as starting points in PDIPM (with TCSC)		Results obtained by default starting points of primal/dual interior point method (without TCSC)	
	Active power spot price (\$/MWh) (Case A)	Reactive power spot price (\$/MVARh) (Case B)	Active power spot price (\$/MWh) (Case C)	Reactive power spot price (\$/MVARh) (Case D)	Active power spot price (\$/MWh) (Case E)	Reactive power spot price (\$/MVARh) (Case F)
Gen1	12.233	0.242	12.033	0.232	12.492	0.219
Gen2	11.868	0.320	11.929	0.410	11.565	0.396
Gen3	11.984	1.063	11.990	0.887	11.877	1.183
Load 4	13.137	0.980	12.428	0.420	15.674	4.345
Load 5	12.663	0.596	12.522	0.490	12.939	1.169
Load 6	12.307	0.326	12.286	0.307	12.206	0.423

Cases A, C and E are graphically depicted in Fig. 5.1. It can be seen that optimally placed TCSC increases real power spot prices at generator buses 2 and 3. Thus, it increases producers' surplus.

Also, it decreases real power spot prices at load buses 4, 5 and 6. So, consumers have to pay less charges for the energy they have consumed. Thus, consumers' surplus increase.

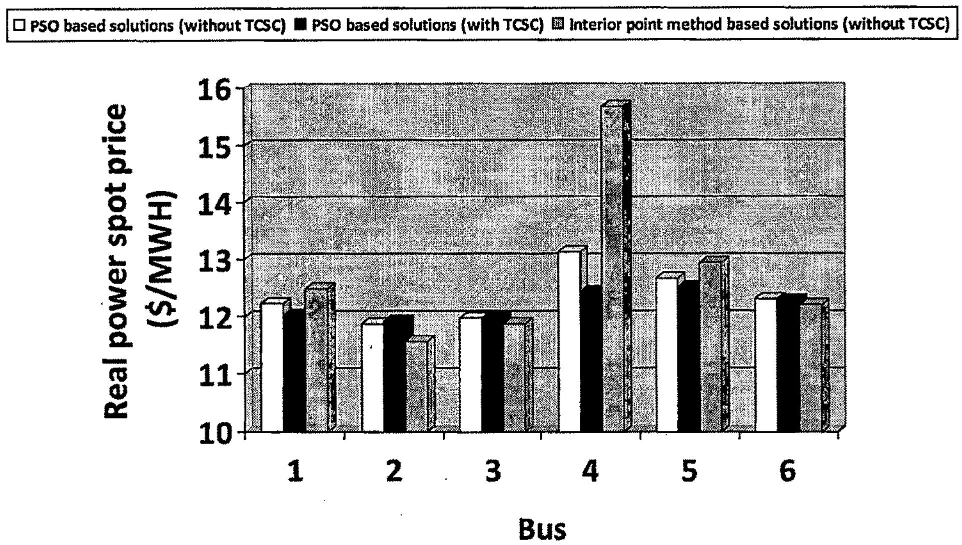

Figure 5.1: Comparison of real power spot price obtained from PSO based starting points and default starting points in interior point method

Cases B, D and F are graphically depicted in Fig. 5.2. It is seen that optimally placed TCSC reduces reactive power spot prices at all load buses i.e. 4, 5 and 6. It also increases reactive power spot prices at generator buses 1 and 2.

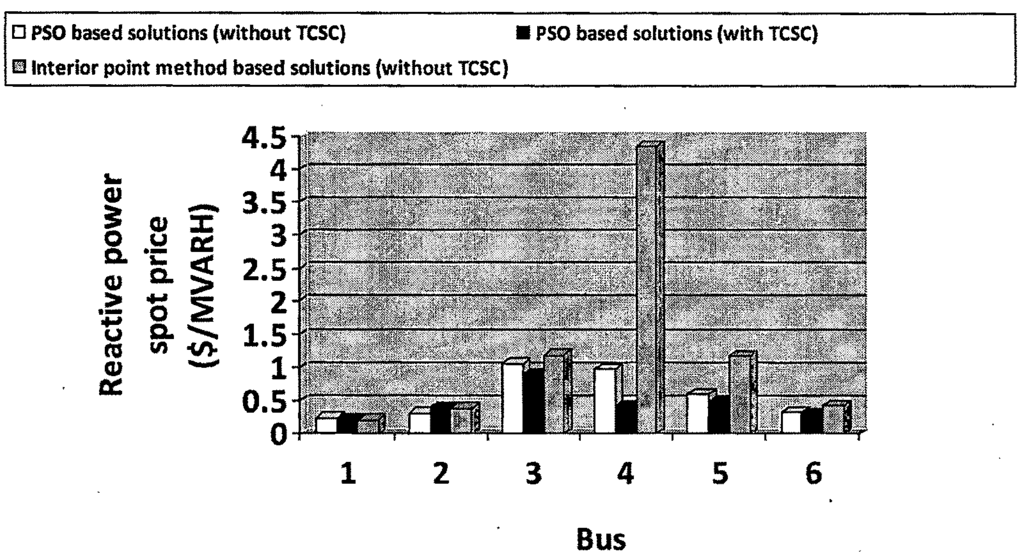

Figure 5.2: Comparison of reactive power spot price obtained from PSO based starting points and default starting points in interior point method

Table 5.3 shows the wheeling charges for real power of various bilateral transactions. Comparing the results of 2nd column with 4th column reveals that most of the wheeling charges obtained by PSO have lesser value than those obtained by IP method. For transaction between bus 3-6 wheeling charge obtained by PSO is grater than that of Interior point method, because load at bus 6 is responsible for large power flow in some transmission lines which increases its spot price. When TCSC is optimally placed by PSO, it significantly reduces wheeling charges (15.45 \$/MWH) for real power. For transaction between bus 2-4, highest reduction in wheeling charge is obtained because the value of load at bus 4 is such that it requires less power flow in some transmission lines and TCSC reduces losses to a great extend and thus wheeling charge is significantly reduced. Wheeling charges are graphically depicted in Fig. 5.3.

Table 5.3: Real power wheeling charges (\$/MWh) of selected bilateral transactions

Seller bus-Buyer bus	Wheeling charges obtained by PSO		Wheeling charges obtained by Interior point method
	Without TCSC (\$/MWh)	With TCSC (\$/MWh)	Without TCSC (\$/MWh)
1-4	22.77	13.58	105.48
1-5	8.96	8.29	12.11
2 − 4	**60.20**	**20.40**	**164.60**
2-5	14.87	11.57	23.09
2-6	10.52	8.76	15.69
3-5	16.86	13.72	23.35
3 − 6	**15.83**	**15.45**	**15.28**

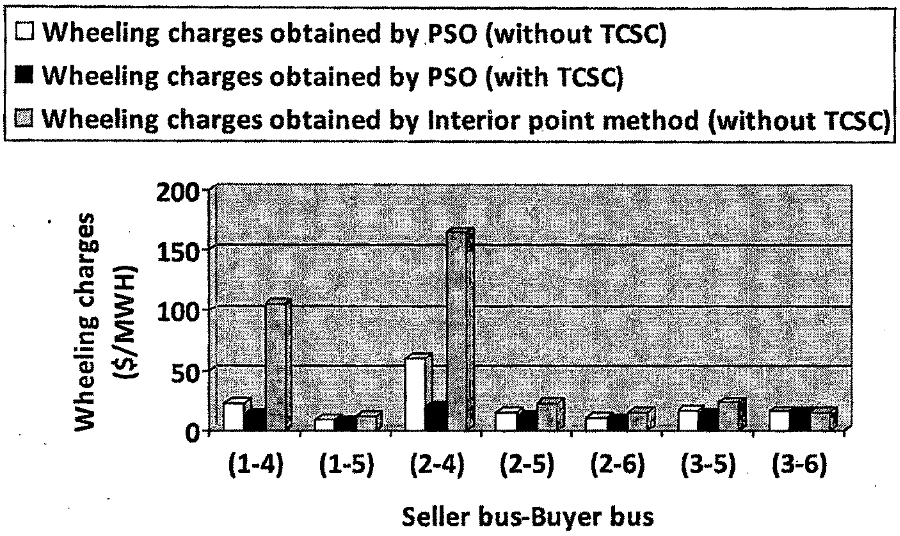

Figure 5.3: Real power wheeling charges ($/MWh) of selected bilateral transactions

Table 5.4 and Fig. 5.4 show the wheeling charges for reactive power of various bilateral transactions. It can be seen that even though the spot price of reactive power are very less as compared to that of real power spot price, the wheeling charge of reactive power is quite significant and should be considered while formatting the bilateral contracts. Wheeling charge of reactive power for transaction between bus 2-6 becomes negative after placing TCSC. So buyer bus 6 will get discount for purchasing reactive power from seller bus 2. So TCSC encourages buyer bus 6 to reschedule its load in such a way that it may even get more discount from the transaction. Comparing cases G and I, it can be seen that wheeling charges obtained by PSO are lesser than those obtained by Interior Point method. So, GENCOs and DISCOs will have to pay less charges to the transmission owner for using transmission infrastructure. Case H clearly indicates that optimally placed TCSC further reduces wheeling charges. So, market players can increase their savings from the transactions.

Table 5.4: Reactive power wheeling charges ($/MVARh) of selected bilateral transactions

Seller bus-Buyer bus	Wheeling charges obtained by PSO		Wheeling charges obtained by Interior point method
	Without TCSC ($/MVARh) (Case G)	With TCSC ($/MVARh) (Case H)	Without TCSC ($/MVARh) (Case I)
1-4	24.41	6.207	96.79
1-5	8.4	5.216	15.39
2-4	21.87	0.350	165.18
2-5	4.366	1.530	13.496
2 – 6	**0.105**	**–2.320**	**0.442**
3-5	-9.34	-7.241	-0.339
3-6	-39.42	-28.112	-43.183

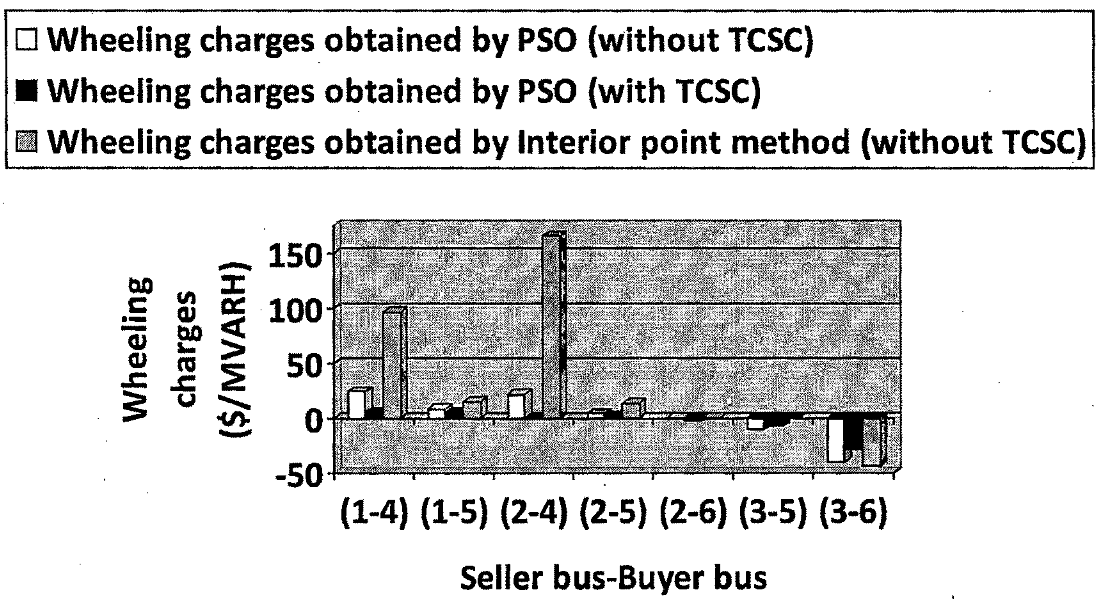

Figure 5.4: Reactive power wheeling charges ($/MVARh) of selected bilateral transactions

Table 5.5 and Fig. 5.5 show the proposed bilateral transaction matrix. The elements of the table represent the bilateral contract between the i^{th} seller bus (generator bus) and j^{th} buyer bus (load bus). The elements in the table have positive real values. Some contracts between the generator bus and load bus have zero values. The secure bilateral transaction matrix is obtained from the proposed bilateral transaction matrix after performing optimization.

Table 5.5: Effect of TCSC on bilateral transaction matrix

Proposed bilateral transactions (T)(MW) between the seller bus and buyer bus	Secure bilateral transactions (T) (MW) obtained by PSO	
	without TCSC	with TCSC
T(1,4) :35	25.19	34.39
T(1,5) :40	20.85	16.97
T(1,6) :0	0	0
T(2,4) :35	47.44	40.89
T(2,5) :20	18.71	19.52
T(2,6) :20	23.97	24.55
T(3,4) :0	0	0
T(3,5):10	24.84	24.87
T(3,6):50	49.04	48.91

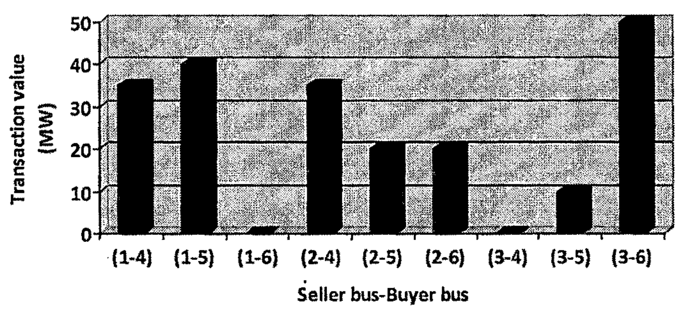

Figure 5.5: Proposed bilateral transaction matrix (without TCSC)

Fig. 5.6 shows the comparison of secure bilateral transaction matrix obtained without and with using TCSC. It can be seen that optimally placed TCSC increases the values of more than 50% secure bilateral transactions. So, DISCOs can re-arrange their load demand to get maximum profit from the transactions. It can also be seen that the pattern of secure bilateral transactions is more uniform in the presence of TCSC. It is because of power flow control capability of TCSC.

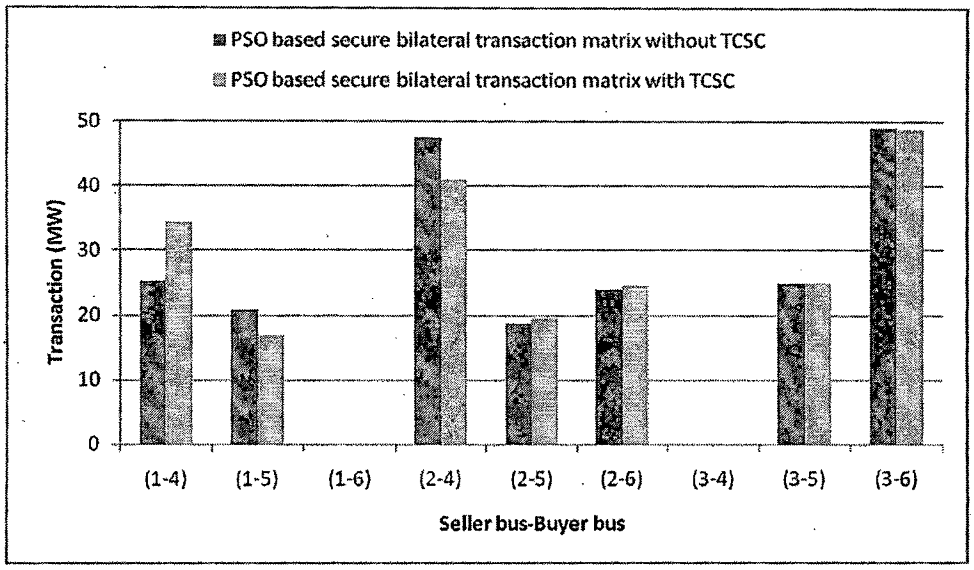

Figure 5.6: Effect of TCSC on secure bilateral transaction matrix

Fig. 5.7 shows the comparison of secure bilateral transaction matrix obtained by Interior point method and PSO method. It is seen that PSO can fulfill more contractual demand than interior point method in most of the transactions. It is because PSO could simultaneously optimized generators' active power outputs and generators' bus voltages, whereas interior point method could not do the same.

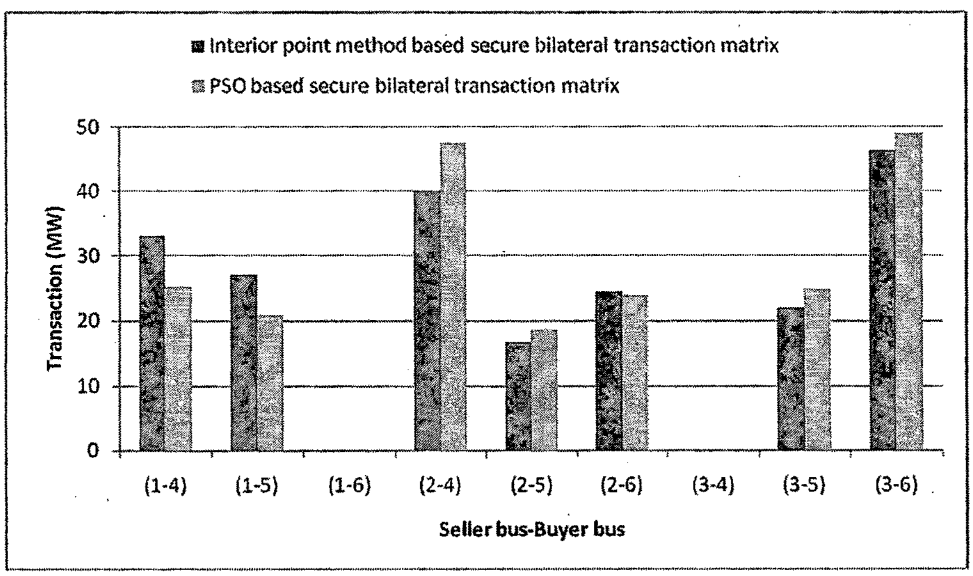

Figure 5.7: Comparison of secure bilateral transaction matrix obtained by Interior point method and PSO

5.8.2 IEEE 30-bus test system

The data of 30-bus system [3] consists of 6 generators and 41 transmission lines. In Table 5.6, Real power spot price and Reactive power spot price (Locational Marginal Price) at each generator bus and load bus is given. It is seen that the spot prices of real power are very high as compared to that of reactive power. Optimally placed TCSC reduces real power spot price and reactive power spot price of all load buses, whereas it increases both spot prices of almost all generator buses. It is because TCSC redistributes power flow in the transmission lines in such a way to decrease the losses and thus it tries to equalize spot prices at various load buses.

Table 5.6: Active and reactive power spot prices with and without using TCSC

Bus No.	Without TCSC		With TCSC	
	Active power spot price (\$/MWh)	Reactive power spot price (\$/MVARh)	Active power spot price (\$/MWh)	Reactive power spot price (\$/MVARh)
gen 1	3.213	0.1873	3.401	0.200
gen 2	3.337	0.2546	3.421	0.265
load 3	3.385	0.010	3.756	0.005
load 4	3.432	0.007	3.334	0.004
gen 5	3.564	0.459	3.700	0.475
load 6	3.461	0.365	3.276	0.323
load 7	3.529	0.019	3.453	0.008
gen 8	3.457	0.344	3.765	0.543
load 9	3.468	0.401	3.273	0.365
load 10	3.467	0.028	3.207	0.024
gen 11	3.464	0.3873	3.647	0.345
load 12*	—	—	—	—
gen 13	3.427	0.454	3.564	0.546
load 14	3.488	0.021	3.253	0.020
load 15	3.507	0.036	3.483	0.032
load 16	3.468	0.028	3.234	0.026
load 17	3.479	0.035	3.283	0.029
load 18	3.546	0.052	3.501	0.045
load 19	3.553	0.057	3.550	0.047
load 20	3.535	0.051	3.501	0.048
load 21	3.502	0.051	3.487	0.047
load 22	3.502	0.050	3.549	0.047
load 23	3.540	0.060	3.523	0.058
load 24	3.552	0.075	3.510	0.072
load 25	3.525	0.043	3.510	0.041
load 26	3.591	0.087	3.563	0.085
load 27	3.482	0.007	3.472	0.004
load 28	3.480	0.362	3.453	0.341
load 29	3.578	0.034	3.563	0.032
load 30	3.645	0.045	3.623	0.041

* It is an internal bus of a three winding transformer

Fig. 5.8 shows the impact of optimally placed TCSC on the magnitude of active power wheeling charges of some selected bilateral transactions. It can be seen that wheeling charges of bilateral transactions (2-6), (8-6), (11-9) and (8-28) have +ve values. i.e consumers connected at bus 6, 9 and 28 will have to pay energy charges to the transmission owner for the utilizing transmission infrastructure, if TCSC is not installed in the power system. But after installing TCSC, the values of wheeling charges of selected bilateral transactions become negative which indicates that consumers connected at bus 6, 9 and 28 will get discount for purchasing active power from their respective sellers. So, TCSC encourages consumers to reschedule their loads in such a way that they may get even more discount from the transactions.

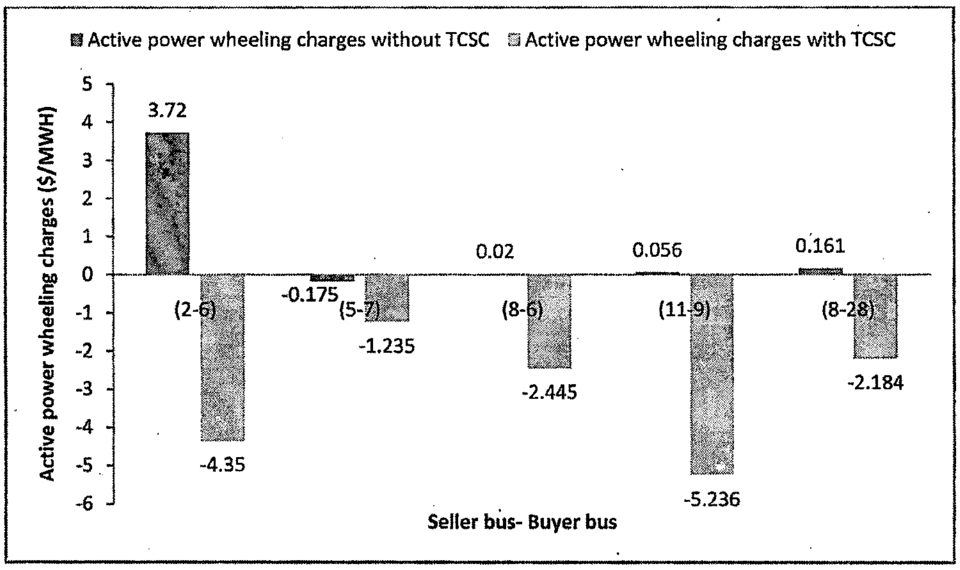

Figure 5.8: Active power wheeling charges without and with TCSC

Fig. 5.9 shows the impact of optimally placed TCSC on the magnitude of reactive power wheeling charges of some selected bilateral transactions. For most of the transactions except between bus (11-9), reactive power wheeling charges are decreased due to placement of TCSC. So for those transactions, buyers will get discount for purchasing reactive power from their respective suppliers. So, TCSC encourages consumers to reschedule their reactive power demand in such a way that they may get even more discount from the transactions.

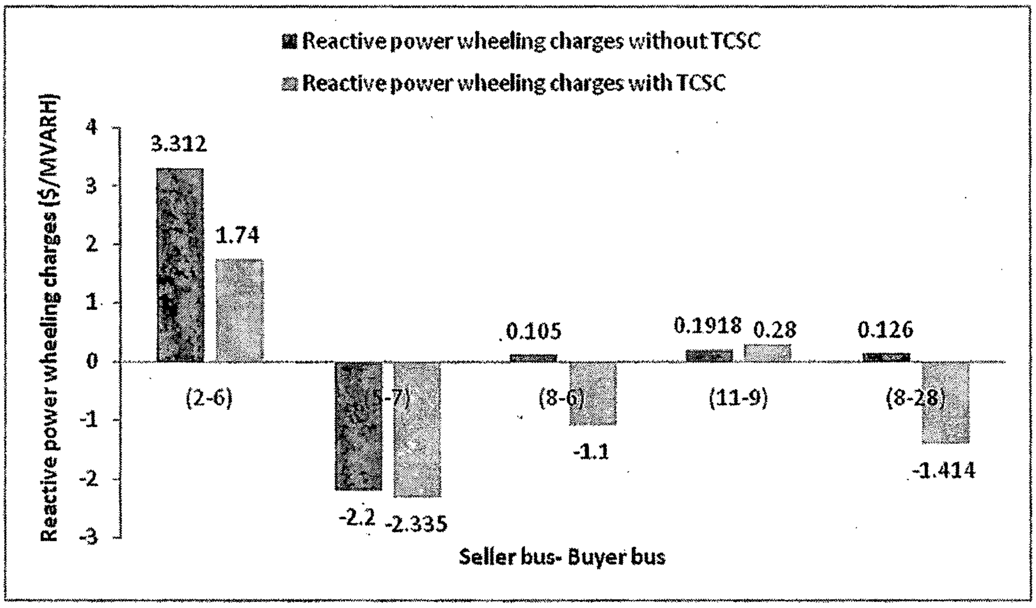

Figure 5.9: Reactive power wheeling charges without and with TCSC

Table 5.7 shows the proposed bilateral transaction matrix between the various seller and buyer buses. A bilateral transaction of 30 MW has been scheduled between the seller bus 2 and buyer bus 6.

Table 5.7: Proposed bilateral transaction matrix

Sr no.	Seller bus-Buyer bus	Transaction (MW)
1	(2-6)	30
2	(5-7)	5
3	(8-6)	5
4	(11-9)	14
5	(13-12)	19.5
6	(8-28)	7

Table 5.8 shows the effect of TCSC on secure bilateral transaction matrix. The bilateral transactions have been obtained without and with the presence of TCSC. From Fig. 5.10it can be seen that the pattern of secure bilateral transaction becomes more uniform in the presence of TCSC. It is because of power flow control capability of TCSC. Whereas, in the absence of TCSC the pattern of bilateral transactions is not uniform.

Table 5.8: Secure bilateral transaction matrix

Sr no.	Seller bus-Buyer bus	Transaction (MW)	
		Without TCSC	With TCSC
1	(2-6)	33.28	29.79
2	(5-7)	20.23	24.18
3	(8-6)	10.04	15.28
4	(11-9)	13.84	15
5	(13-12)	17.89	20
6	(8-28)	5.71	8.2

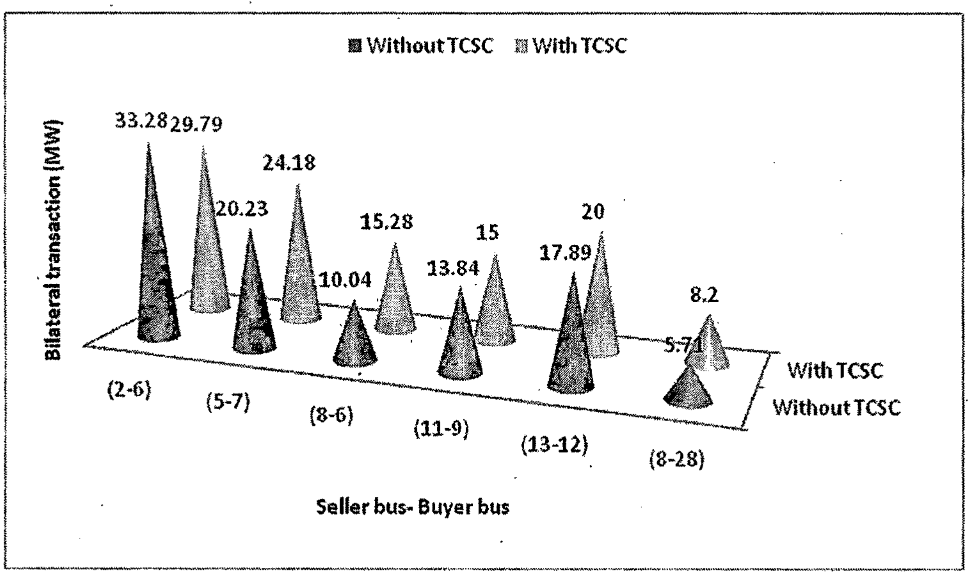

Figure 5.10: Effect of TCSC on secure bilateral transaction matrix

5.8.3 UPSEB 75-bus test system

This system consists of 15 generator buses, 60 load buses and 95 transmission lines. As shown in Fig. 5.11, active power spot prices of the generator buses have been obtained without using TCSC and with TCSC. It is clear that spot prices at the generator buses are increased after installing TCSC. As a result GENCOs can obtain more revenue from the various bilateral transactions and thus they can increase their profit.

Fig. 5.12 shows active power spot prices of all load buses without using TCSC and with TCSC. It can be seen that optimally placed TCSC significantly reduces spot prices of the load buses. So consumers will have to pay less energy charges for the consumption of active

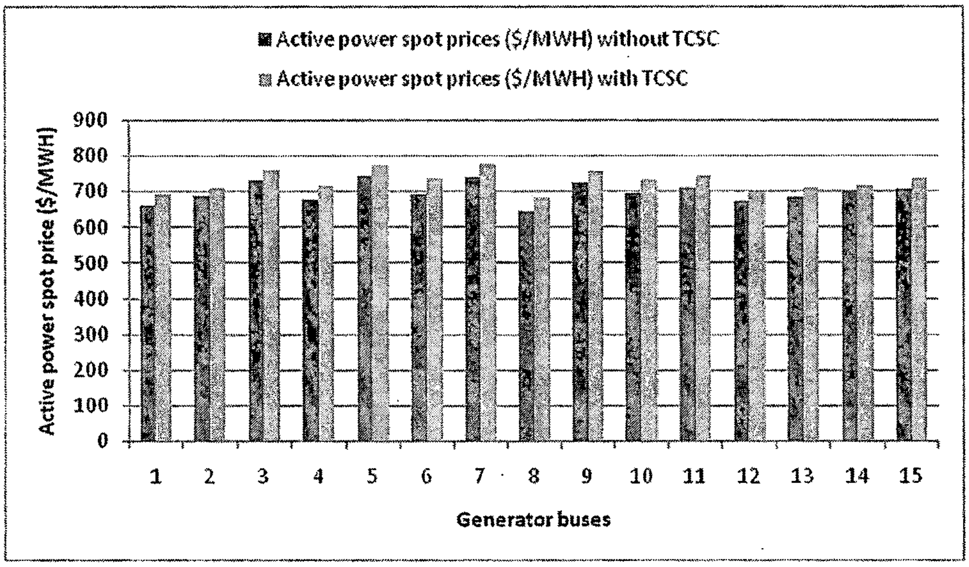

Figure 5.11: Active power spot prices (\$/**MWh**)) of generator buses

power in the presence of TCSC. So optimal placement of TCSC is also beneficial to the consumers. The nature of graph of spot prices in the presence of TCSC is more uniform than that of without TCSC. It is because optimally place TCSC redistributes power flow in the transmission lines in such a way to decrease the losses and thus it tries to equalize spot prices at various load buses.

Fig. 5.13 shows the reactive power spot prices of all generator buses without using TCSC and with TCSC. The spot prices are increased at the generators 5,6,9,11,12,14 and 15 after placing TCSC, whereas for remaining generator buses they are decreased.

Fig. 5.14 shows the reactive power spot prices of all load buses without using TCSC and with TCSC. It can be seen that spot prices at bus 18 and 40 became more negative after placing TCSC, whereas for remaining load buses they got decreased after placing TCSC.

Fig. 5.15 shows the active power wheeling charges of some selected bilateral transactions without using TCSC and with TCSC. It can be observed that for transaction (2-16) wheeling charge was increased after placing TCSC, whereas for remaining transactions the values of wheeling charges were decreased after placing TCSC. It is because TCSC reduces losses of the system and it removes congestion of the transmission lines. So it is quite beneficial to the supplier and consumer of electricity as they have to pay less amount to the transmission owner for the usage of transmission infrastructure.

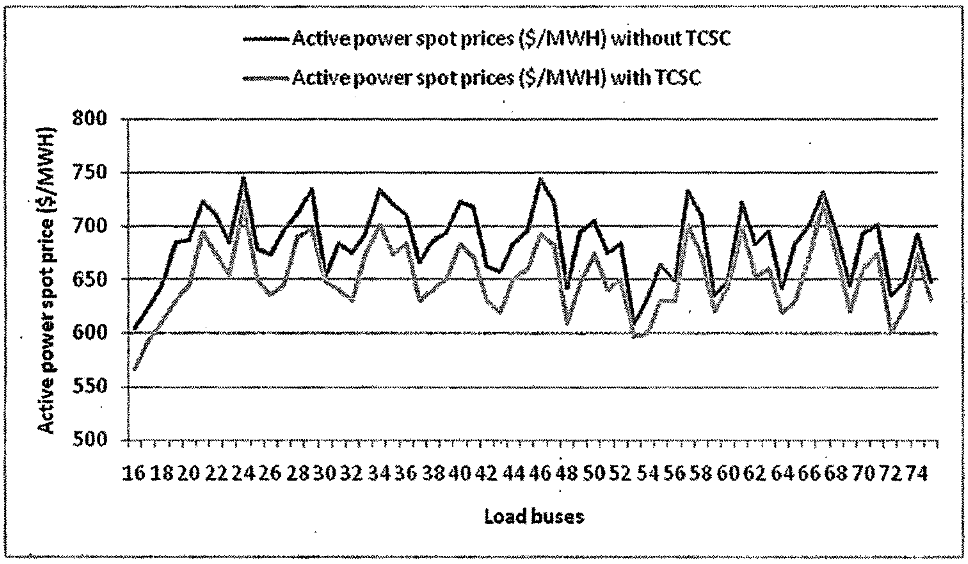

Figure 5.12: Active power spot prices($/**MWh**)of load buses

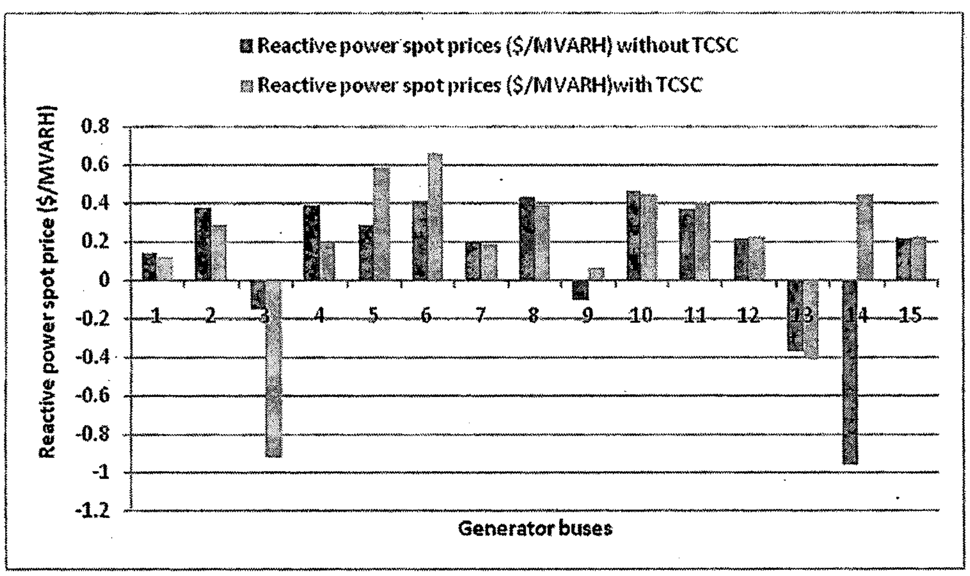

Figure 5.13: Reactive power spot prices ($/**MVARh**) of generator buses

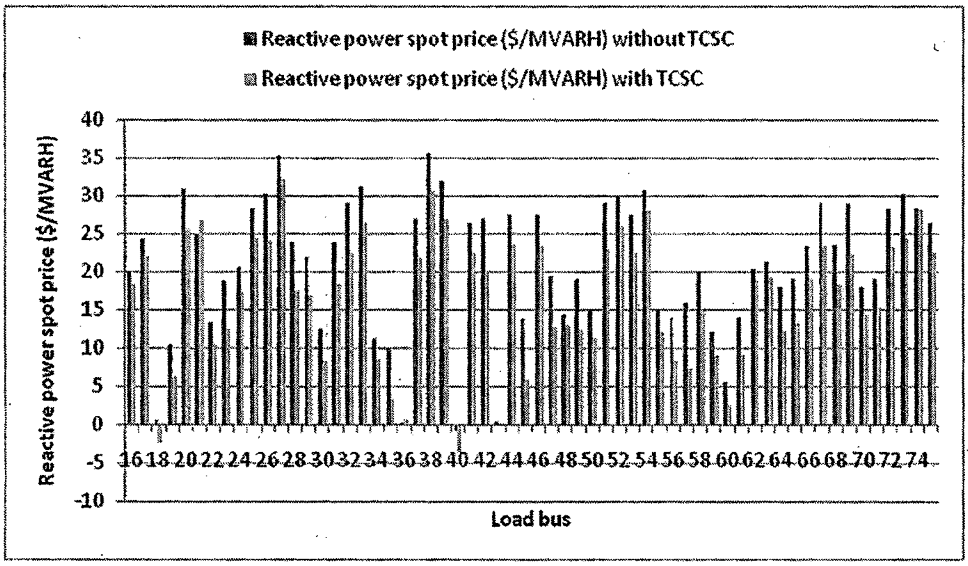

Figure 5.14: Reactive power spot prices ($/MVARh) of load buses

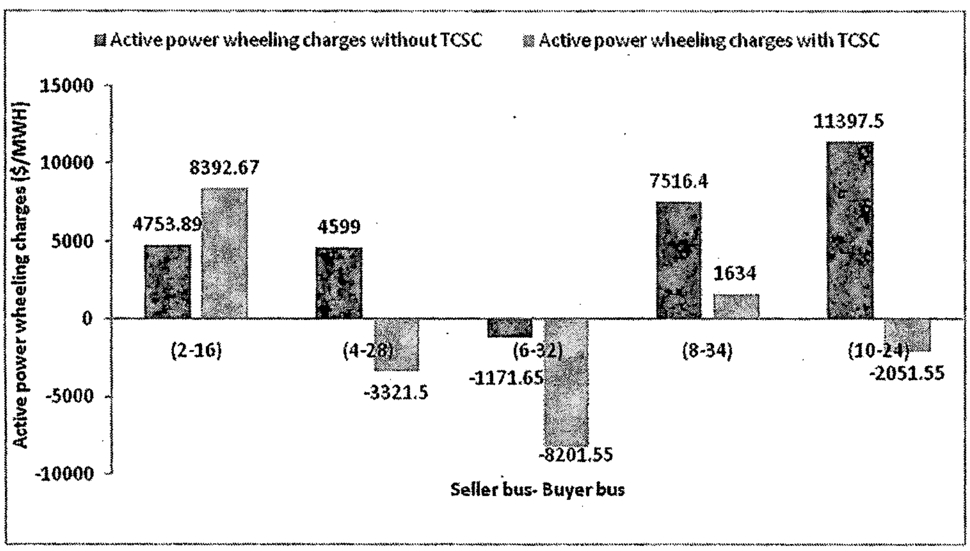

Figure 5.15: Active power wheeling charges without and with TCSC

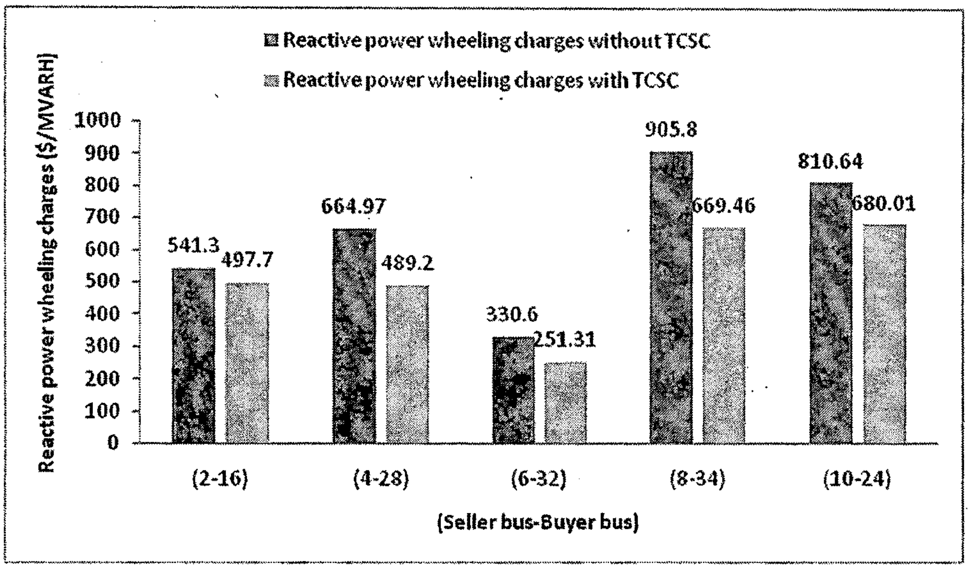

Figure 5.16: Reactive power wheeling charges without and with TCSC

Fig. 5.16 shows the reactive power wheeling charges of some selected bilateral transactions with and without using TCSC. It is inferred that wheeling charges for all transactions have been reduced after placing TCSC. So GENCOs and DISCOs will have to pay less reactive wheeling charges to the transmission owner for the usage of transmission lines.

Fig. 5.17 shows the proposed and secure bilateral transactions with and without using TCSC. It can be clearly seen that the pattern of secure bilateral transactions becomes more uniform in the presence of TCSC.

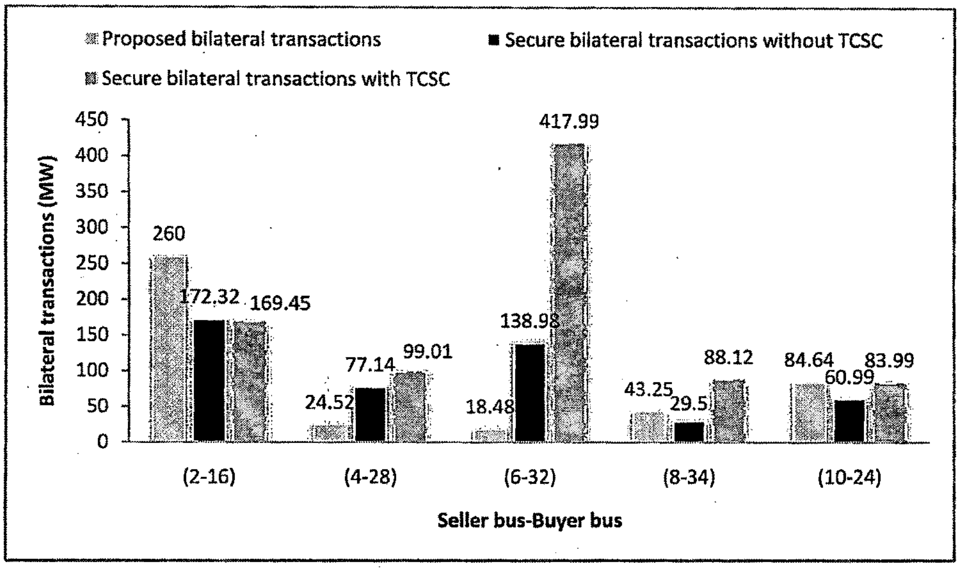

Figure 5.17: Proposed and secured bilateral transactions

5.9 Conclusions

This chapter has investigated the impact of optimally placed TCSC on transmission pricing (Spot prices), active and reactive power wheeling charges and secure bilateral transactions. The simulations were carried out on IEEE 6-bus, IEEE 30-bus and practical UPSEB 75-bus systems. The contribution of this chapter to the available literature can be concluded as follows:

1. Optimally placed TCSC could significantly increased active power spot prices and reactive power spot prices at the generator buses and decreased them at the load buses.

2. TCSC remarkably decreased active and reactive power wheeling charges of various bilateral transactions. So it is concluded that placement of TCSC is very much beneficial to the GENCOs and DISCOs because they have to pay less charges to the transmission owner for the usage of transmission infrastructure.

3. The pattern of secure bilateral transaction matrix has been obtained with and without optimally placed TCSC. It is seen that the pattern of secure bilateral transactions is

different for with and without TCSC due to different power flow through the transmission lines. The pattern of secure bilateral transactions becomes more uniform in the presence of TCSC. Hence, the obtained transaction matrix will enable Independent System Operator (ISO) to obtain better dispatch results to meet bilateral demands and reserving the bilateral transactions within the available transfer capability for increasing the operational efficiency of the deregulated electricity market.