Chapter 1

Introduction

1.1 General

The electric power system, throughout the world, has evolved as a large integrated network during the last century. Traditionally, electric power system has been dominated by large utilities those have an overall control in generation, transmission and distribution of power within their region of operation. Such utilities have been generally referred as vertically integrated utilities. These utilities served as the only electricity provider and were obliged to provide electricity to all in a region. These state-owned monopolistic structures of electric utilities were essential for development, expansion and standardization of the electric power industry during earlier days. These goals have been almost achieved and the electric utility has matured enough to drive itself.

The existing rules of the monopolistic market authorize a single utility to generate, transfer, distribute and sell electricity in a region, state and a country. Utilities have to operate according to the government policies, guidelines and regulations; and are assured of fair returns without bearing any risk. In most part of the world, this has led to incompetence and lethargic attitude in the industry as they lack motivation for technical innovation, managerial inefficiency and customer focus. In order to nullify these drawbacks of the monopolistic market, most of the utilities are undergoing restructuring.

According to [147], Deregulation is a restructuring of the rules and economic incentives that governing authority sets up to control and drive the electric power industry. Deregulation of power systems is expected to offer the benefit of lower electricity price through competition, better consumer service and improved system efficiency. However, it posses several technical challenges with respect to its conceptualization and integrated operation. Basic issues of insuring economic, secure and stable operation of the power system are superimposed by an economic market management. Thus, technical issues are incorporated with economical issues, which make them very complex as compared to those of traditional monopolistic electricity market.

Power systems, all over the world, have been forced to operate in almost their full capacities due to the economical, environmental and political constraints to build new generating stations and transmission lines. The amount of electric power that can be transmitted between two buses through a transmission grid is limited by security constraints. Power flow should not be allowed to increase to a level where a random event could cause the grid to collapse because of angular stability, voltage instability and cascaded outages. The transmission grid is said to be congested when such limit is reached. Also, all market players try to get the benefits of cheaper source and greater profit margins, which may lead to congestion of certain part of a transmission system. Congestion management is the most basic and the top priority management problem which the system operator has to face very frequently. So, managing congestion to minimize the restrictions of the transmission grid in the deregulated market has become the central activity of the Independent System Operator.

Semiconductor technology enabled the manufacture to make powerful thyristors, Gate turn-off thyristors (GTO) and Insulated gate bipolar transistor (IGBT). So, development based upon semiconductor devices first invented High voltage DC transmission (HVDC) technology which could be used as an alternative to long distance AC transmission lines. Eventually, the same technology has provided the basis for the development of Flexible AC Transmission System (FACTS) devices, which may be used to solve various problems of the deregulated power system.

The deregulation of the electric utility has opened the door for a great number of large and small Independent Power Producers (IPP) across the power system. There is a need of Independent System Operator (ISO) also to manage the transmission network, its operation, security and reliability while ensuring its open access to all market participants in free and transparent manner. Since the transmission system is shared by all market participants, ISO needs to know the status of Total Transfer Capability (TTC) to fulfill contractual demand [13]. This situation also calls for effective methods to ensure the transmission system reliability and to control the power flow among different parts of the network. Thyristor Controlled Series Compensator (TCSC) is the versatile FACTS device which can nullify many problems of power system optimization due to its faster control action and adaptive capabilities. The applications of TCSC to power system optimization problems have been an attraction in ongoing research work.

This chapter has presented an overview of current trends of a restructured electrical power system in section 1.2, Working principle of TCSC and its role in open power market in section 1.3. Finally, detailed literature survey on the topic of research has been presented in section 1.4, while the motivation behind the present thesis work and organization of the thesis has been given in the sections 1.5 and 1.6, respectively.

1.2 Restructured electrical power system and its models

In the last two decades, many electric utilities have been forced to operate in different ways from vertically integrated functioning to open market systems. The reasons for restructuring have been many and differ across various countries. In developing country like India, the main issue has been high rise in demand associated with inefficient system management, lack of funds for capital investment, and irrational tariff policies. This has affected the availability of capital investment in generation and transmission systems. In such a situation, many countries are forced to restructure their power sectors under pressure from the international funding agencies. On the other hand, in the developed countries, the driving force has been to provide the customers with electricity at lower prices and to offer them greater choice and flexibility.

The restructuring of electricity market has changed the role of traditional entities of the vertically integrated utility and created new entities that can function independently. The market entities can be broadly classified into:

- Market participants
- Independent System Operator (ISO)

A brief introduction of various market participants are given below:

1.2.1 Generating Companies (GENCOs)

GENCOs generate electricity and have the opportunity to sell the electricity to entities with which they have negotiated sales contracts. Generally GENCOs consist of a group of generating units within a single company ownership structure with the sole objective of producing electrical power. In addition to active power, they may sell reactive power (ancillary services) and operating reserves.

1.2.2 Transmission Companies (TRANSCOs)

It transports electricity using a high voltage, bulk transmission system from GENCOs to Distribution Companies (DISCOs)/retailers for delivering power to customers. A TRANSCO has role of building, owning, maintaining and operating the transmission system in a certain geographical region to provide services for maintaining the overall reliability of the electrical power systems and provides open access of transmission wires to all market entities in the system. The investment and operating costs of transmission facilities are recovered using access charges, which are usually paid by every user within the area/region, and transmission usage charges based on line flows contributed by each user.

1.2.3 Distribution Companies (DISCOs)

A distribution company (DISCO) distributes the electricity, through its facilities, to customers in a certain geographical region. They buy wholesale electricity either through the spot markets or through direct contracts with GENCOs and supply electricity to the end-user customers. A DISCO is a regulated utility that constructs and maintains distribution wires connecting the transmission grid to the end user customers. A DISCO is responsible for building and operating its electric system to maintain a desired degree of reliability and availability.

1.2.4 Customers

A customer is the end-user of electricity with certain facilities connected to the distribution system in the case of small customers, and connected to transmission system in case of bulk customers. In a restructured system, customers are no longer obligated to purchase electricity from their local utility company and have several options to buy electricity. It may choose to buy electricity from spot market by bidding for purchase or through direct contracts with GENCOs or even from the local distribution company with the best overall value.

1.2.5 Market Operator

A market operator is an entity responsible for operation of electricity market trading. It receives bids from the market participants and determines the market price based on certain criteria in accordance with the market structure. The markets may have different trading schemes such as hourly trading for the next day or trading in future weeks, months and years ahead.

1.2.6 Independent System Operator (ISO)

A competitive market would necessitate an independent operation and control of the grid. Due to this reason, most of the utilities have established an entity called Independent System Operator. It is entrusted with responsibility of ensuring the reliability, security and efficient operation of an open access transmission system [15]. It administers transmission tariff, maintains system security, coordinates maintenance scheduling, and has a role in coordinating long term planning. It is an independent authority and does not participate in trading of electricity. The ISO has the authority to commit and redispatch the system resources and to curtail loads for maintaining the system security i.e. to remove the transmission violations, balance supply and demand, and maintain the acceptable system frequency. This responsibility of ISO forms the basis for the functionality of the Transmission Dispatch and Congestion Management System. ISO can procure various ancillary services such as supply of emergency reserves or reactive power from other entities in the system to maintain reliability. In general, there are two possible structure of ISO[142] and the choice of the structure depends on the ISO's objective and authority. These structures are:

- Min ISO
- Max ISO

Min ISO is mainly concerned with maintaining transmission security in the operation of the power market to the extent that ISO is able to schedule power transfers in a constrained transmission system. This structure is based on coordinated multilateral trades and has no role in the market administration. California Independent System Operator (CAISO) is an example of this structure. Max ISO includes a power exchange, which is an independent non-government and non-profit entity that ensures a competitive market place for electricity trades. It performs the functions like deciding and posting of Market Clearing Price (MCP). The Pennsylvania New Jercy Marryland (PJM) SO and National Grid Company (NGC) are the examples of this structure.

1.2.7 Aggregators

An aggregator is an entity or a firm that combines customers into a buying group. The group buys large blocks of power and other services at cheaper prices. The aggregator may act as an agent between customers and retailers.

1.2.8 Brokers

A broker of electric energy services is an entity or firm that acts like a middleman in a market place in which these services are priced, purchased and traded. A broker does not take a title on available transactions, generate, purchase, or sell electric energy, but facilitate transactions between buyer and seller. A broker may act as an agent between GENCOs and DISCOs.

1.2.9 Retail Companies (RETAILCOs)

A RETAILCO obtaines legal approval to sell retail electricity. A retailer buys electric energy and other necessary services to provide electricity to its customers and may combine electricity products and services in various packages for sale. A retailer may deal indirectly with end-use customers through aggregators.

Fig. 1.1 shows a typical structure of a deregulated electricity system with links of information and money flow between various players.

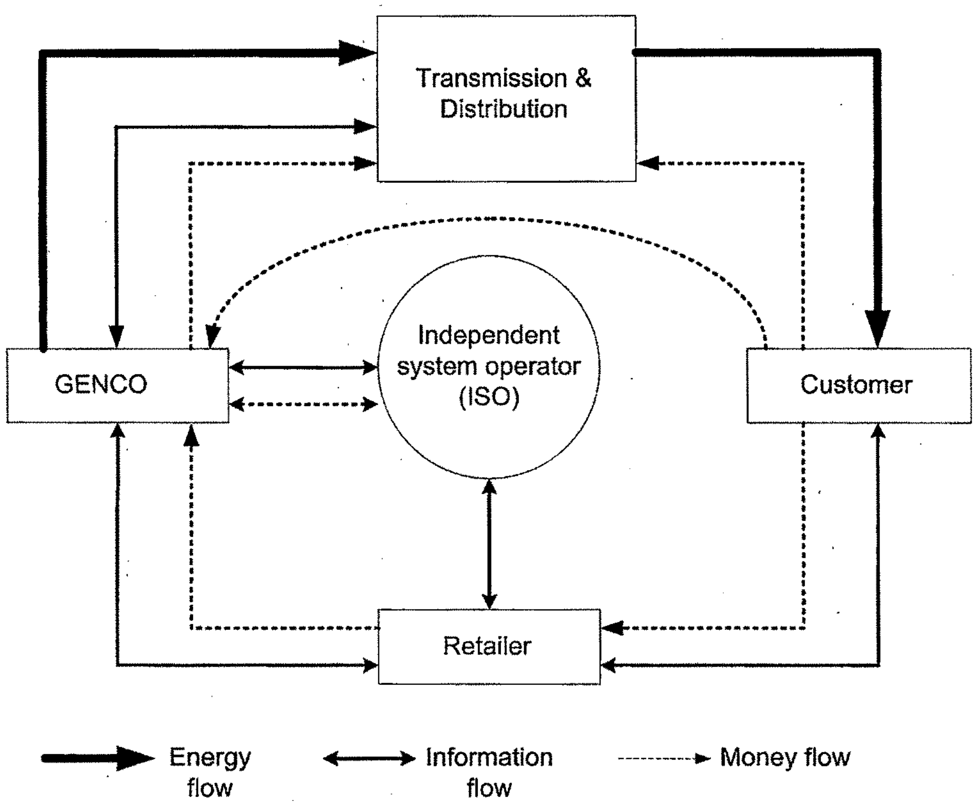

Figure 1.1: Deregulated electricity market model

Based on trading quantities, the competitive markets may include separate energy market, ancillary service market and the transmission market.

1.2.10 Energy market

In an energy market, the competitive trading of electric energy occurs. The energy market is a centralized mechanism that facilitates energy trading between sellers and buyers. ISO or the Power Exchange (PX) operates the energy market. In the Min SO model, the SO or PX accepts the demand and generation bids (a price and quantity pair) from the market participants, and determines the MCP at which energy is to be bought and sold. In the Max SO model, market participants must submit extensive information similar to that required in regulated industries, such as energy offer, start-up cost, no-load costs etc. From these data, SO implements security-constrained unit commitments and economic dispatch that maximizes social welfare.

1.2.11 Ancillary service market

According to North American Reliability Council (NERC), an ancillary service is an interconnected operation service that is necessary to effect a transfer of electricity between purchasing and selling entities, and which a transmission provider must include in an open access transmission tariff. Ancillary services are needed for the power system to operate reliably. In the deregulated market, the ancillary services are mandated to be unbundled from the energy services. Ancillary services are procured through the market competitively. The six ancillary services are:

- Regulation service
- Load following service
- Contingency reserve service
- Reactive power support service
- Frequency regulation service
- System black start service

- Loss makeup
- Spinning reserve

1.2.12 Transmission market

In a restructured power system, transmission network plays an important role to transfer power. The commodity traded in the transmission market is the transmission right. This may be the right to transfer power, the right to inject power into the network, or the right to extract the power from the network. The transmission right auction would represent a centralized auction in which the market participants submit their bids for purchase and sale of right. The auction is conducted by SO and its objective is to determine bids that would be feasible in terms of transmission constraints and that would maximize revenues for transmission network use.

Several market structure and transactions exist to achieve a competitive electricity environment. Three basic models based on the types of transactions are outlined as follows [144].

1.2.12.1 PoolCo model

A PoolCo is defined as a centralized market place that clears the market for the buyers and sellers. Electric power sellers/buyers submit bids to the pool for the amount of power that they are willing to trade in the market. Thus, under this model, one single entity, the Pool Company (usually system operator), purchases the power from the competing generators in the open market and generally sells it at a single market clearing price to the retailers or consumers. Sellers in a power market would compete for the right to supply energy to the grid, and not to specific customers. In this market, low cost generators would especially be rewarded.

1.2.12.2 Bilateral Contract model

In a deregulated electricity market structure, under competition and open access, the different transactions may take place directly between buyers and sellers. A bilateral transaction is an exchange of power between buying and selling entities [14]. These transactions can be

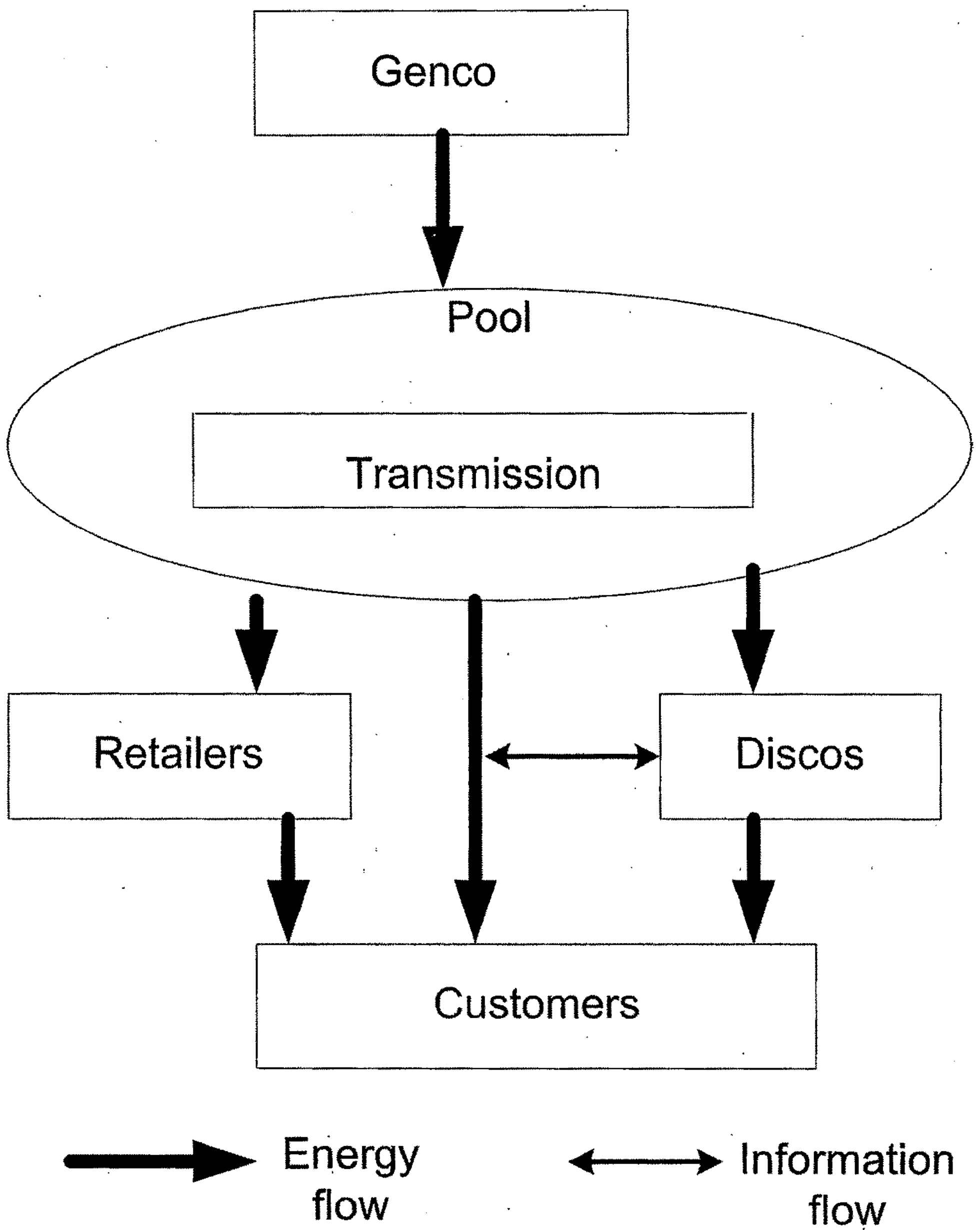

Figure 1.2: PoolCo Model

defined for a particular time interval of the day and its value may be time varying. It may be either firm or non-firm and can be a short term and long term transaction. The bilateral contract model may include different kinds of transactions as given below:

- Bilateral Transactions: A bilateral transaction is made directly between a GENCO and a DISCO without any third party intervention.
- Multilateral Transactions: A multilateral transaction is a trade arranged by energy brokers and involves more than two parties. Multilateral transactions are the extension of bilateral transactions and may take place between a group of sellers and a group of buyers at different buses.
- Ancillary services transactions: The SO may directly make some transactions with some GENCO in order to provide essential ancillary services for system regulation.

1.2.12.3 Hybrid model

The hybrid model combines various features of the previous two models. In the hybrid model, the utilization of the PoolCo is not obligatory, and any customer would be allowed to negotiate a power supply agreement directly with the suppliers or choose to accept power at the pool market price. In this model, PoolCo will serve all participants (buyers and sellers), who choose not to sign bilateral contracts. However, allowing customers to negotiate power purchase agreements with suppliers would offer a true customer choice and an impetus for creation of wide variety of services and the pricing options to best meet individual customer needs.

1.3 Main FACTS controller

In general, FACTS controllers can be divided into four categories:

1. Series controller
2. Shunt controller
3. Combined series-series controller

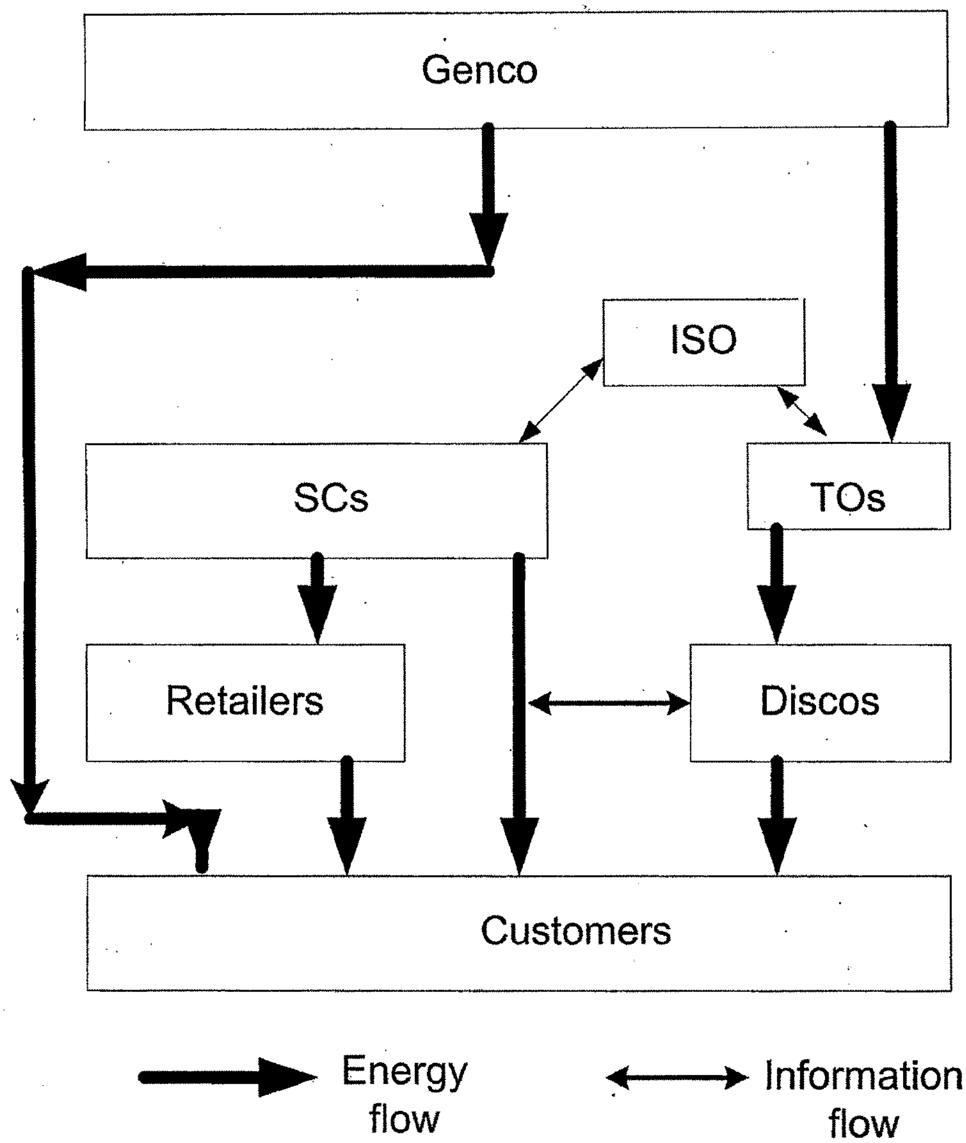

Figure 1.3: Bilateral/Multilateral model

4. Combined series-shunt controller

In [145], the various configuration of FACTS devices has been given in detail. However, a brief description of TCSC is given below, because its application has been suggested in this thesis.

1.3.1 Thyristor Controlled Series Compensator (TCSC)

The basic Thyristor Controlled series compensator scheme is a method of "rapid adjustment of network impedance". It is shown in Fig 1.4. It consists of the series compensating capacitor shunted by a Thyristor-Controlled reactor. In a practical TCSC implementation, several such basic compensators may be connected in series to obtain the desired voltage rating and operating characteristics. The basic idea behind the TCSC is to provide a continuously variable capacitor by means of partially canceling the effective compensating capacitance by the TCR. The TCR at the fundamental system frequency is a continuously variable reactive impedance, controllable by delay angle (α), the steady-state impedance of the TCSC is that of a parallel LC circuit, consisting of a fixed capacitive impedance (X_c), and a variable inductive impedance($X_L(\alpha)$), that is:

$$X_{TCSC(\alpha)} = \frac{-jX_cX_{L(\alpha)}}{X_{L(\alpha)} - X_c} \tag{1.1}$$

Let,

X_l= Original reactance of the line

k= $\frac{X_{TCSC(\alpha)}}{X_l}$= Degree of series compensation provided by the TCSC, $0 \leq k \leq 1$

$$X_{L(\alpha)} = X_L \times \frac{\pi}{\pi - 2\alpha - sin\alpha}, X_L \leq X_{L(\alpha)} \leq \infty \tag{1.2}$$

$X_L = \omega L = X_{TCR}$is the reactance of the core reactor ,

$X_c = \frac{1}{2\pi fC}$= reactance of the capacitor

$\alpha$is the delay angle measured from the crest of the capacitor voltage,

X_{TCSC}= The impedance of TCSC

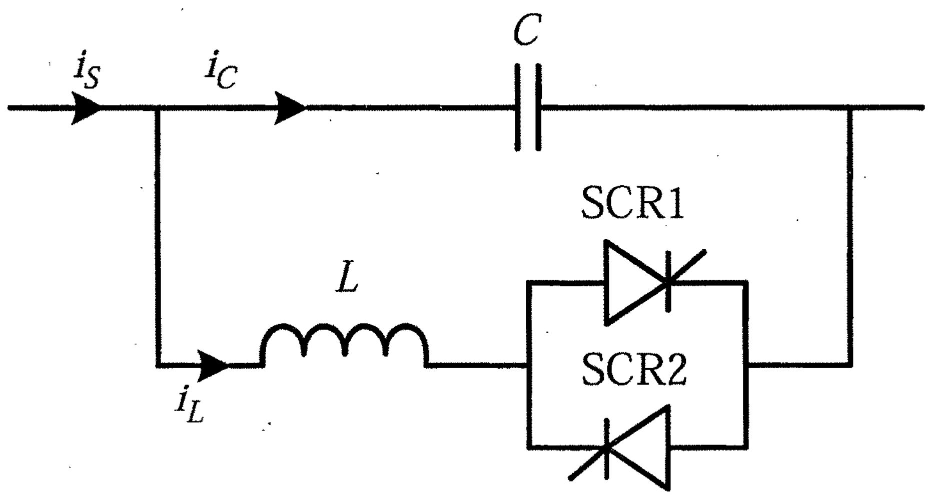

Figure 1.4: Equivalent circuit of TCSC

- When $X_c < X_L$, X_{TCSC} will be capacitive. I_{TCR} is 180° out of phase with line current

- when $X_c > X_L$,X_{TCSC} will be inductive. I_{TCR} is in phase with line current

1.3.1.1 Operating modes of TCSC

The different operating modes of TCSC are discussed below.

1. Bypassed Thyristor Mode: In this mode, the thyristors are made to conduct fully with a conduction angle of 180 degree. Gate pulses are applied as soon as the voltage across the thyristor reaches zero and becomes positive, resulting in continuous sinusoidal flow of current through the thyristor. The TCSC module behaves like a parallel capacitor-inductor combination. This mode is used mainly for protecting the capacitor against overvoltage (during transient over current in the line). This mode is also termed as TSR (thyristor switched reactor) mode. Fig.1.7 shows the operation of TCSC in bypassed thyristor mode.

2. Blocked Thyristor Mode: In this mode, no current flows through the valves with the blocking of gate pulses. Here, the TCSC reactance is the same as that of the fixed capacitor and there is no difference in the performance of TCSC in this mode with that of a fixed capacitor. Hence, this operating mode is generally avoided. This mode is

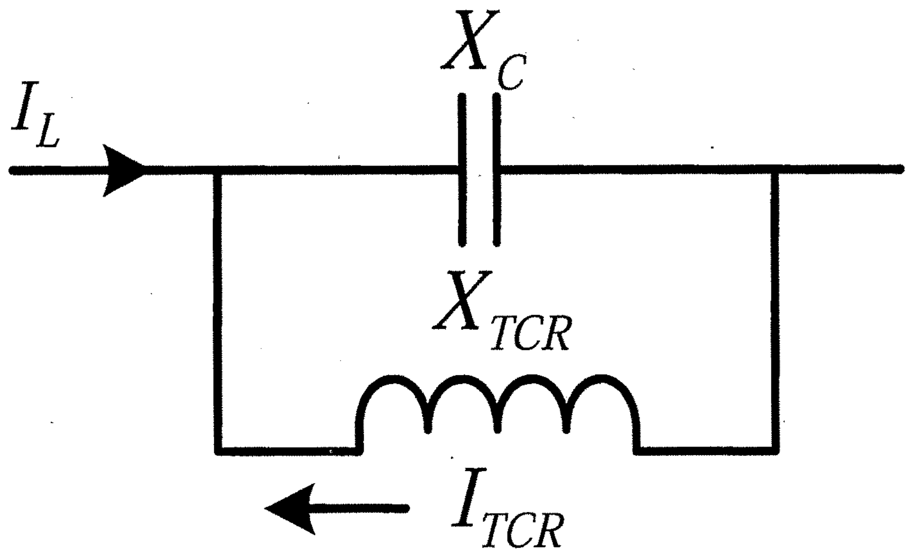

Figure 1.5: Capacitive mode of TCSC

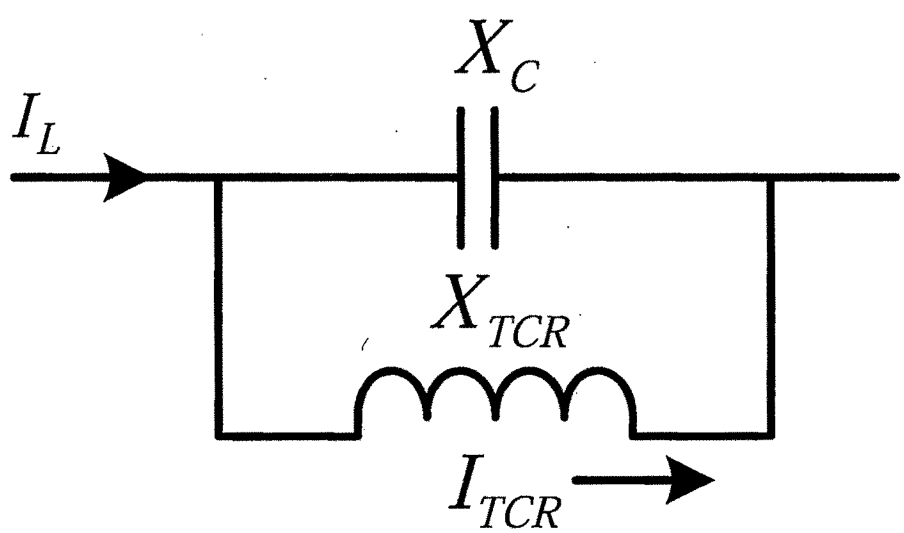

Figure 1.6: Inductive mode of TCSC

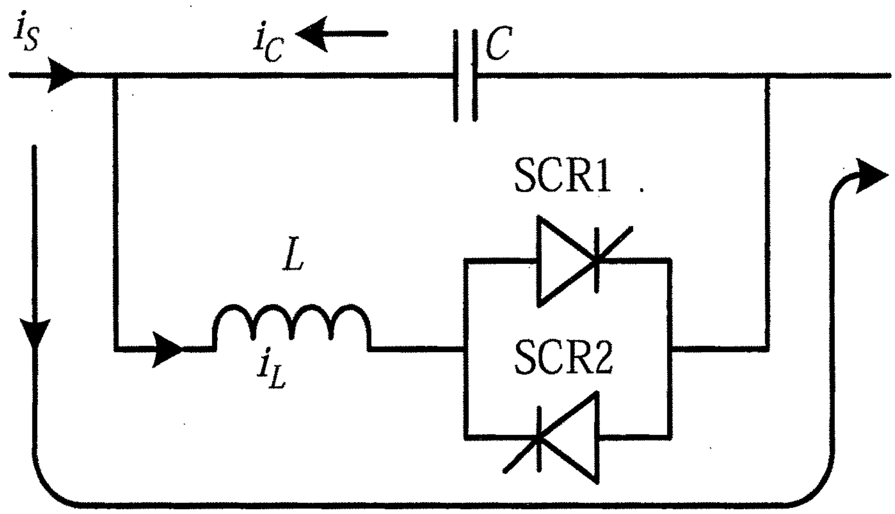

Figure 1.7: Bypassed thyristor mode

also termed as waiting mode. Fig.1.8 shows the operation of TCSC in blocked thyristor mode.

3. Partially Conducting Thyristor or Vernier Mode: In this mode, the thyristors valves are gated in the region of , such that they conduct for the part of a cycle. The effective value of TCSC reactance (in the capacitive region) increases as the conduction angle (σ) increases from zero. is more than the value of (α) corresponding to the parallel resonance of TCR and the capacitor at fundamental frequency. In the inductive vernier mode, the TCSC (inductive) reactance increases as the conduction angle reduces from 180 degree. Generally, vernier control is used only in the capacitive region and shown in Fig. 1.9.

The impedance vs. delay angle characteristic of the TCSC is shown in Fig. 1.10. Basically, the TCSC presents a tunable parallel LC circuit to the line current that is substantially a constant alternating current source. As the impedance of the controlled reactor ($X_L(\alpha)$), is varied from its maximum towards its minimum, the TCSC increases its minimum capacitive impedance, $X_{TCSC,min}=X_c=1/\omega C$, until parallel resonance at $X_c=X_L(\alpha)$is established and $X_{TCSC,max}$theoretically becomes infinite. Decreasing $X_L(\alpha)$further,the impedance of the TCSC, $X_{TCSC}(\alpha)$becomes inductive, reaching its minimum value of $\frac{X_L X_c}{X_L - X_c}$ at α=0, where the

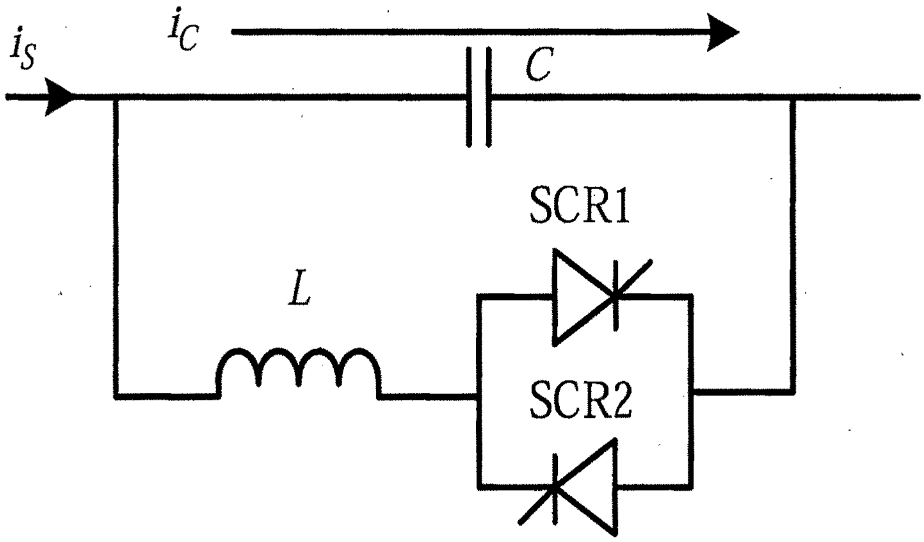

Figure 1.8: Blocked thyristor mode

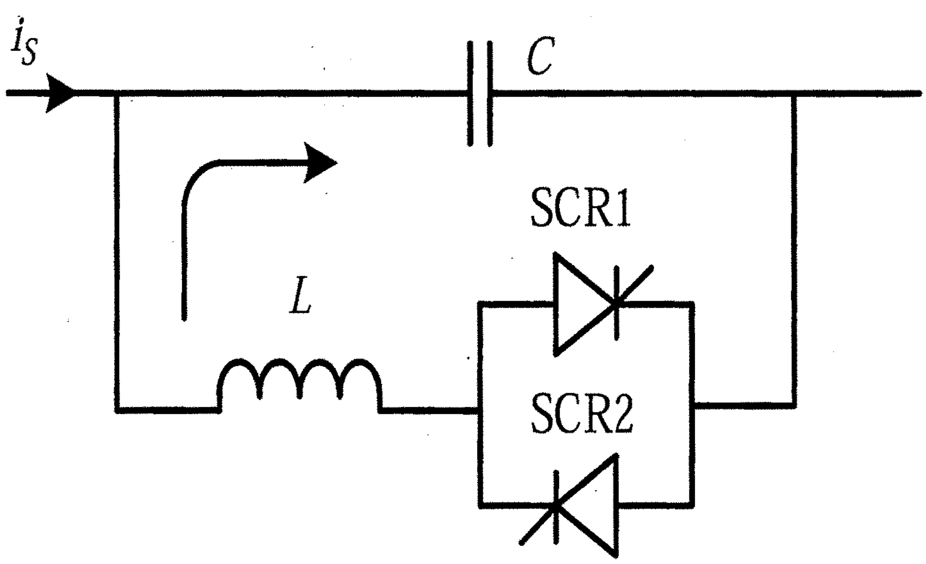

Figure 1.9: Vernier mode

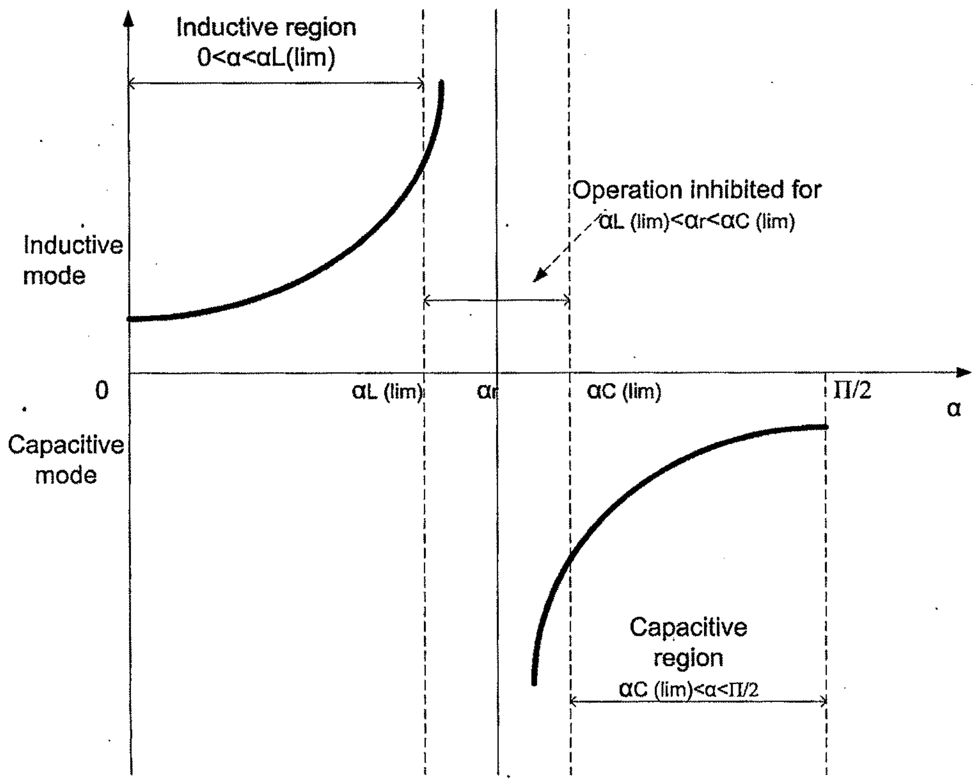

Figure 1.10: The impedance vs. delay angle(α)characteristic of the TCSC

capacitor is in effect bypassed by the TCR. So, with the usual TCSC arrangement in which the impedance of the TCR reactor (X_L) is smaller than that of the capacitor (X_c), the TCSC has two operating ranges around its internal circuit resonance: One is the $\alpha_{clim} \leq \alpha \leq \Pi/2$ range, where $X_{TCSC}(\alpha)$ is capacitive, and the other is the $0 \leq \alpha \leq \alpha_{Llim}$range, where $X_{TCSC}(\alpha)$ is inductive.

1.4 State-of-the-Art

Operation and control of a restructured electricity market poses technical challenges, which are far more complex than those in the conventional monopolistic electricity market. The complexity arises due to involvement of several market entities, satisfaction of many types of contractual obligations, separation of primary and ancillary services, and varying models of electricity markets. Some of the technical challenges include:

- Optimal placement of TCSC

- Determination of TTC
- Social welfare and pricing of energy
- Congestion management
- Ancillary service management
- Transaction allocation

This thesis has mainly addressed the two issues viz. Optimal placement of TCSC for optimizing various objectives and transmission congestion management. A representative survey of literature on these two issues, relevent to work carried out in this thesis, is presented below.

1.4.1 Optimal placement of FACTS for maximization of TTC and minimization of losses

Various methods have been developed so far for determining TTC with and without using FACTS devices in open market. G.C. Ejebe et al. [13] proposed continuation power flow for determining hourly TTC and ATC but It requires effective parametrization of predictor, corrector and step length to obtain global solution. The computational effort required is too large. It uses common loading factor to increase generation and load which may result in a conservative TTC. M.H.Gravener et al. [19] used repeated power flow method to determine ATC. It was a simple method but it did not optimize generator output power and its voltage. K.S.Verma et al. [34] proposed sensitivity based approach to optimally locate FACTS devices to enhance TTC. Ying Xiao et al. [57] used predictor corrector primal duel interior point linear programming to enhance ATC using various FACTS devices. However it did not optimize their ratings and locations. M. Shaaban et al. [60] proposed SQP based method to find TTC incorporating the effect of reactive power but it required the calculation of Hessian matrix in each iteration which was too time consuming. Weixing Li et al. [95] used sequential quadratic programming to calculate probabilistic TTC considering different contingency states. But this method required second order derivative of the objective function. P. Jirapong et al. [101] proposed hybrid evolutionary algorithm to optimally place multi-type FACTS devices like UPFC, TCSC, SVC and TCPAR to maximize TTC. M. Rashidinejad et al. [110] proposed real genetic algorithm to optimally locate two TCSC for enhancing ATC of IEEE 9-bus and 30-bus systems. Venkatesh et al. [66] used Power Transfer Distribution Factors for determining ATC and results were compared with Newton-Raphson method. A Kumar et al. [73] proposed bifurcation approach to determine ATC in the presence of SVC. S. Mollazei et al [102] used modified PSO method to maximize TTC and to minimize voltage deviation using TCSC in 5 area test system.

From the literature survey it is revealed that with the inclusion of FACTS control variables, the "optimal placement of FACTS devices" becomes highly nonlinear and non-convex optimization problem which can not be effectively solved by the classical methods as they may get trapped into local minima or diverge at all. To solve such problem, an artificial intelligent method called Particle Swarm Optimization [8] has been used as it is a fast method and it provides global solution. PSO has shown its superiority over other classical and AI methods with respect to execution time and global solution in solving economic dispatch problem [87] and optimal reactive power dispatch problem [82].

1.4.2 Social welfare maximization

Various classical and artificial intelligence methods have been suggested to optimally locate FACTS devices with different kinds of objective functions. Lin et al. [24]used interior point method for system expansion with UPFC to maximize social welfare and to manage congestion. Gerbex et al.[29] used genetic algorithm for multi-type FACTS placement to enhance system loadability. However, number of devices to be installed was assigned before optimization and installation cost was ignored. Lima et al.[55] used Mixed Integer Linear Programming to find optimum number, locations and setting of TCPST to optimize loadability and investment with respect to dc load flow model. Yu et al. [75] used Mixed Integer Non-linear programming for optimal location of FACTS to maximize social welfare based on multiple time periods. But it ignored the impact of FACTS on reactive power flow. Xiao et al.[58] used predictor corrector primal duel interior point linear programming to enhance ATC using various FACTS devices. However, it did not optimize their ratings and locations. Verma et al.[94] used sensitivity based approach to study the impact of UPFC on real and reactive power spot prices. Jirapong et al.[101] proposed hybrid evolutionary algorithm to optimally place multi-type FACTS devices to maximize TTC and minimize losses. 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. Yang et al.[103] used Mixed-Integer Quadratic programming to find optimal location of TCSC for enhancing system loadability, voltage profile considering its investment cost. Singh et al.[100] proposed reactive power spot price index to place SVC to minimize total generation cost and to maximize loading margin. Rashidinejad et al.[111] proposed real genetic algorithm to optimally locate two TCSC for enhancing ATC and to get best voltage profile. But generators' active output powers and bus voltages were not optimized. Sharma et al.[125] used mixed integer nonlinear programming to locate UPFC to maximize system loadability for pool and bilateral electricity markets.

So, it is revealed that most of the OPF problems are non-linear and non-convex. With the inclusion of FACTS control variables, they become even more nonlinear because they change the size of bus admittance matrix and dimension of the problem. Conventional classical optimization methods like gradient method, lamda iteration, linear programming etc. rely on the convexity assumption of objective function. They fail to capture discontinuities of objective function and may get trapped into local minima or diverge at all. Choice of initial starting point also affects the quality of solution. Also, they could find only a single optimized solution in a single simulation run. Thus, to find global optimum solution is a challenging task in nonlinear optimization problem incorporating FACTS devices. So in this paper, PSO based algorithm has been suggested to find the best location and setting of TCSC to maximize social welfare and to minimize total generation cost while satisfying various constraints. 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 same algorithm can be modified to maximize social benefit without considering TCSC. Comparisons are carried out with solutions obtained from Non-linear programming method (MINOS [86]) used in MATPOWER [105].

1.4.3 Impact of FACTS devices on pricing, wheeling charges and secure bilateral transactions

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. Baughman et al.[6] developed an OPF model by introducing reactive power pricing and revealed that Lagrange multipliers, corresponding to node power balance equations in optimal power flow, represent the marginal costs of node power injections. They claimed that OPF was a promising tool for spot pricing. In[143], a program structure based on OPF was introduced to compute the decomposition of spot prices. Oliviera et al.[17] have shown the ability of FACTS devices to change the production cost and their impact on spot prices. They concluded that the effect of FACTS devices on transmission charge varies according to the pricing methodology adopted. They considered production cost minimization as the objective function. UK Lim et al.[23] presented a new operation scheme of UPFC's to minimize power production and delivery costs. In normal operation state of power system, the production costs of active power can be minimized by economic dispatch, and delivery costs due to transmission system loss can be minimized by active power control of UPFC, incorporated with minimization of production cost. 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.

So, 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 generator active power output, generator bus voltages, TCSC setting and TCSC location. Generators' cost functions and consumers' bid functions are considered separately. Secondly, out of many suggested 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, optimized outputs obtained from PSO method have been 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 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.

1.4.4 Congestion management

Various algorithms and methods for congestion management have been proposed so far. In [11], congestion costs of pool and bilateral models were minimized considering active power redispatching of generators. But, it ignored the effect of losses and reactive power. Fang et al. [18] proposed a method of willingness to pay to avoid curtailment of bilateral transaction. In [12], an analytical tool named Transmission Dispatch and Congestion Management System had been developed to help ISO to manage congestion. In [35], FACTS devices like TCSC and TCPAR were used to manage congestion efficiently. They have used sensitivity based approach to locate those FACTs devices. Padhy [71] proposed hybrid fuzzy model to determine optimal transactions and their corresponding load curtailment for managing congestion. Kumar et al. [78] suggested real and reactive power flow sensitivity indexes to identify different congested zones. Generators' output powers and reactive power of optimally placed capacitor were rescheduled to minimize rescheduling cost. Talukdar et al. [85] proposed a method for selecting loads to be curtailed out and participating generators, based upon their sensitivities to the overloaded lines. However, reactive power was not rescheduled to remove congestion. Acharya et al.[98] established LMP difference and congestion rent based concept to locate TCSC to reduce congestion. In[104], Relative Electrical Distance based concept was introduced for real power rescheduling. But, the generators with same RED would contribute same power to congested line. In this case, the cost was not optimized if both generators had different cost functions. In [99], multiobjective PSO was used to alleviate congestion from maximum number of lines and minimize cost of generation. In [108], PSO was used to minimize rescheduling cost of active power. However, the effects of rescheduling cost of reactive power and voltage stability constraints were ignored. The purpose of this work is to suggest an efficient method for selecting number of participating generators and optimum rescheduling of active and reactive power outputs of generators for managing congestion at minimum rescheduling cost. Generally, all generators do not have the same effect (sensitivity) on the power flow of a congested line. So in practical situation, only a few generators take part in removing congestion. So firstly, active power and reactive power sensitivity factors of generators to the congested line are found out. The number of participating generators is selected from sensitivity factors. Secondly, active and reactive power rescheduling of participating generators are optimally done in such a way that the total active and reactive power rescheduling costs get minimized. Sometimes, congestion alleviation results into larger voltage deviations or very low voltage profile at load buses, which may invite voltage collapse. So, voltages of generators have been rescheduled to keep load bus voltages within permissible limits. PSO has been used to solve such nonlinear OPF, as classical methods have many limitations in solving such problem. The PSO based algorithm has been tested on IEEE 30-bus and UPSEB 75-bus test systems.

1.5 Motivation

From the literature survey, it is clear that various methods used to determine TTC uptil now are as follows: Continuation power flow[13], repeated power flow[19], sensitivity based approach[34], interior point method[57], sequential quadratic programming[95], evolutionary programming method[101] and genetic algorithm method[110]. TTC directly gives the maximum possible transaction and this information has to be continuously displayed on website of OASIS. Thus, TTC needs to be calculated very fast and accurately. Secondly, TCSC can play an important role in enhancing TTC due to its power flow control capability. But, as it is a costly device, it is very important to optimally locate it to obtain its full benefits. Thirdly, TCSC can significantly reduce losses of the transmission lines by changing reactance of the line. Literature survey reveals that there is no suggestion for a simple, accurate and fast method for determining the optimal location of a TCSC to simultaneously maximizing TTC and minimizing losses of the power system.

Social welfare maximization is the main aim of any deregulated power system which includes consumer surplus and producer surplus. Lin et al. [24] used interior point method for system expansion with UPFC to maximize social welfare. Yu et al. [75] used Mixed Integer Non-linear programming for optimal location of FACTS to maximize social welfare based on multiple time periods. But it ignored the impact of FACTS on reactive power flow. Yang et al.[103] used Mixed-Integer Quadratic programming to find optimal location of TCSC for enhancing system loadability and voltage profile considering its investment cost. TCSC can increase surplus of various market participants. Installation cost of the TCSC should also be minimized and it should be included in the OPF problem. Literature survey reveals that no research work has been carried out in which social welfare has been maximized considering installation cost of TCSC.

Transmission pricing is a vital issue of the deregulated power system. A LMP based approach was used to study an impact of FACTS devices on real and reactive power spot prices [[17], [23]]. Sensitivity and sequential quadratic programming based approach were used to study an impact of FACTS devices on spot prices [[94],[97]]. But, their location and setting were not optimized. Literature survey reveals that no research has been carried out in which the effect of "optimally placed" FACTS devices on pricing has been studied. So, impact of optimally placed TCSC on real and reactive power pricing should be investigated. Transmission prices for both real and reactive powers have been computed with and without TCSC. Secondly, choice of initial starting points greatly affects the convergence of Interior point method[37]. So, there is an interest in suggesting the "best" starting points for the Interior point method to improve its quality of solution. Thirdly, the impact of TCSC on active and reactive power wheeling charges and secure bilateral transactions should be studied.

Congestion management is the highest priority problem that the system operator has to solve in his routine activity. Several congestion management schemes suitable for different electricity market structure have been reported in literature survey. In optimal power flow based method, congestion has been managed by either rescheduling of active power output of generators or curtailing the loads [[11], [18],[71],[99],[108]]. The optimal placement of FACTS controller [35] using sensitivity based approach [[98],[99]] and their role in the congestion management have been also reported. Paper [78] has addressed the role of reactive power in congestion management. From literature survey, it is observed that very few papers have addressed the role of reactive power of the generators in congestion management. Reactive power plays an important role in supporting real power transfer and maintaining voltage stability of the bus bars in the post-rescheduling state. So, reactive power rescheduling of generators should be incorporated in OPF problem. Secondly, all generators do not take part in congestion management. Only a few generators, based upon their active power sensitivities to the congested line have been selected for managing congestion[108]. So, there is a need to develop a method through which reactive power sensitivity factors of the generators to the congested lines may be found out and from those sensitivity factors the number of participating generators whose reactive power have to be rescheduled could be found out.

Hence, the main objectives behind the present work are as follows:

- Development of PSO based algorithm for finding the optimal location and setting of TCSC for maximizing Total Transfer Capability and minimizing transmission losses of the deregulated power system which consists of bilateral and multilateral transactions.

- To develop PSO based algorithm for finding the optimal location and setting of TCSC to maximize social welfare, minimize total generation cost and installation cost of TCSC while satisfying various constraints.

- To investigate the impact of optimally placed TCSC on transmission pricing (Spot prices), active power and reactive power wheeling charges and secure bilateral transactions. Also, to suggest an efficient method which can improve convergence characteristic of an Interior point method.

- To develop simple and efficient method for selecting number of participating generators for managing congestion. So, theory of reactive power generator sensitivity factor has been developed and implemented for selecting the participating generators. In addition, PSO based algorithm has been suggested to minimize active power and reactive power rescheduling costs of participating generators considering voltage stability and voltage profile improvement criteria.

1.6 Thesis Organization

This thesis has been organized into seven chapters. The present chapter 1 introduces the deregulated electricity market, different components and trading models, operating principle of TCSC and its applications in open power market. It represents the relevent state-of-the-art survey and sets the motivation behind the research work carried out in this thesis.

The main focus of chapter 2 was to survey and summarize the applications of Particle Swarm Optimization (PSO) for solving various power system optimization problems like Economic load dispatch, Reactive power management, Optimal power flow, Power system controller design, Neural network training, Price forecasting, Load forecasting, and other areas of power system.

In chapter 3, Enhancement of Total Transfer Capability (TTC) of the deregulated power system has been solved. This chapter has proposed Particle Swarm Optimization (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 consisted of bilateral and multilateral transactions. Impact of various contingencies (e.g. generator outage and line outage) on the value of TTC has been also studied. Simulations were performed on IEEE 30-bus and practical 75-bus Uttar Pradesh State Electricity Board (UPSEB 75) systems.

Chapter 4 has suggested PSO based algorithm to find the best location and setting of TCSC to maximize social welfare, minimize total generation cost and installation cost of TCSC while satisfying various system constraints. Simulations were performed on IEEE 6-bus, IEEE 30-bus and UPSEB 75-bus systems. The results of the proposed method were compared with those of classical method (Nonlinear programming method) and Evolutionary Programming (EP) methods.

Chapter 5 has investigated the impact of optimally placed TCSC on transmission pricing (Spot prices), active and reactive power wheeling charges and secure bilateral transactions. The pattern of secure bilateral transaction matrix has been obtained without and with optimally placed TCSC. Simulations were performed on IEEE 6-bus, IEEE 30-bus and UPSEB 75-bus systems. The simulation results obtained by the proposed method have been compared with those obtained from Primal Dual Interior Point (IP) method.

In chapter 6, Congestion management has been solved by PSO. A sensitivity based method has been suggested for selecting number of generators which took part in managing congestion. Then PSO based algorithm has been suggested for minimizing active power rescheduling cost and reactive power rescheduling cost of selected generators to alleviate congestion in IEEE 30-bus and UPSEB 75-bus test systems, considering voltage stability (L-index) and voltage profile improvement criteria. The simulation results obtained by the proposed method have been compared with those of other published papers.

Chapter 7 summarizes the main findings and significant contributions of the thesis and provides a few suggestions for further research work in this area.