CHAPTER 1

INTRODUCTION

1.1 PRESENT SCENARIO OF ELECTRICITY MARKET

An electric power system comprises of three major sub-systems namely power generation system, transmission system and distribution system. It is the transmission system through which the electrical power generated by the generators is consumed by the loads at the consumer side. To ensure the reliability of power supply to the consumers, the transmission lines are operated at loadings well below their thermal ratings (Tina Orfaxogiannt 2000). In the recent years, the increasing industrialization along with the rapid urbanization of society has resulted in a huge increase in power demand (Saranjeet 2009). In order to cater to this increase in power demand, the capacity of the transmission systems needs to be increased (Gitizadeh 2010). In this scenario, construction of new transmission lines becomes nearly impossible owing to the high investment costs coupled with other factors such as time taken for construction and disruption of the existing system. Consequently, utilizing the maximum capacity of the existing transmission lines becomes very necessary. Hence, aggrandizing the utilization of potential of unused transmission system is one of the main issues in electrical power systems.
1.2 FACTS DEVICES FOR ENHANCING THE TRANSMISSION SYSTEM PERFORMANCE

Presently, the emerging technology of Flexible AC Transmission System (FACTS) is widely used for enhancing the capability of the transmission systems. The concept of FACTS was first defined by Hingorani (1988). FACTS devices are solid state converters that have the capability to control various electrical parameters in transmission circuits. FACTS devices produce rapid response and are environmentally friendly too. A number of FACTS devices have been put forward due to the rapid development of the modern power electronics technology and some of them are Thyristor Controlled Series Compensator (TCSC), Static VAR Compensator (SVC), Unified Power Flow Controller (UPFC) and Static Compensator (Saranjeet 2009). With the installation of FACTS devices, it is possible to increase the power transfer with a marginal investment and within a short gestation period as compared to the construction of new transmission lines (Tina Orfaxogiannt 2000). The potential benefits with the installation of FACTS devices in the transmission network are reduction of operation and transmission costs, increase of system security and reliability, and increase of transfer capabilities of transmission systems (Hingorani and Gyugyi 2000; Mathur and Varma 2002; Watts and Ren 2007).

1.3 SALIENT PERFORMANCE PARAMETERS OF TRANSMISSION SYSTEMS

It is a well known fact that, increase in power demand results in higher transmission loss and lower bus voltages. It is apparent that minimizing the transmission loss leads to the optimum operation of transmission system (Gitizadeh 2010). Power system operators ensure the quality and reliability of supply to the customers by maintaining the load bus voltages within their permissible limits (Vijayapriya et al. 2010). Thus along
with the objective of maximizing the loadability of transmission lines, it
becomes inevitable to consider other objectives such as minimizing the
transmission loss and minimizing the voltage deviation at the load buses for
enhancing the performance of a transmission system.

These objectives can be achieved by the optimal placement of
FACTS devices in the transmission system. This improves the efficiency of
the transmission system and provides a scope for the reduction of the cost of
electrical energy supplied to the consumers. The cost of FACTS devices is
also an important factor to be considered for their optimal placement since
they are costly (Gitizadeh 2010). Hence an objective function without
considering the cost of FACTS devices is not justifiable. Therefore, both
technical and economical objectives are to be considered for the optimal
placement of FACTS devices. Hence the optimal placement of FACTS
devices helps achieving multiple objectives and involves several conflicting
goals.

1.4 FOCUS OF THE RESEARCH

Series capacitive compensation in electrical power systems is
generally recognized as a very economical and powerful means for increasing
long-distance transmission lines’ capability (Flavio Allella et al. 2003). In a
country like India, TCSCs are the major controlling devices for enhancing the
loadability of transmission lines, minimizing the transmission loss and
minimizing the voltage deviation at the load buses. Hence, the focus of this
research falls on the optimal placement of TCSCs with the objectives of
simultaneously maximizing the transmission system loadability and
minimizing the factors such as, transmission loss, cost of TCSCs and voltage
deviation at the load buses.
1.4.1 Optimal Placement of TCSCs

The decision of where to place the TCSCs is largely dependent on the desired effect and the characteristics of the specific system. It is well documented in the literature that the effectiveness of FACTS controllers mainly depends on their locations (Okamoto et al. 1995). The degree of success that can be achieved depends on the choice of the transmission lines in which the TCSCs are installed and the ratings of TCSCs. For this reason, an efficient method for finding the location of TCSCs is desired. Hence a proper placement strategy must precede the installation of TCSCs. In realizing the proposed objectives, the location of TCSCs and their parameters are to be determined simultaneously. Finding the optimal location of a given number of TCSCs and their ratings is a combinatorial optimization problem. To solve such a type of problem, heuristic methods can be used (Sait and Youssef 2000).

1.4.2 Proposed Solution

Finding the optimal location and size of TCSCs is a challenging task as it involves the above mentioned objectives which are conflicting in nature. None of these objectives can be neglected as each objective improves the transmission system operation. Since a practical transmission system consists of a large number of lines, it is difficult to identify the effective location of TCSCs. For solving this problem, an efficient multi-objective optimization technique is required for providing superior pareto optimal solutions. Generally, evolutionary computational techniques are widely applied for solving multi-objective optimization problems because of their simple and powerful, global or near global search capabilities (Krishna Teerth Chaturvedi et al. 2008). This research employs two swarm-intelligence based techniques namely Multi-Objective Particle Swarm optimization (MOPSO) and Multi-Objective Comprehensive Learning Particle Swarm optimizer.
(MOCLPSO) for arriving at the efficient pareto optimal solutions for this multi-objective TCSC placement problem.

1.4.3 Practical Implementation

Multi-objective optimization yields a set of Pareto optimal solutions instead of a single solution. For practical applications, the power system planner has to decide on a single solution from this set of solutions. To help the decision maker in this regard, there exists a wide variety of Multi-Criterion Decision Making (MCDM) techniques in literature. In this research, two different popular MCDM techniques namely, Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and Fuzzy C-Means (FCM) clustering are employed for assisting the decision maker.

1.5 IMPORTANCE OF THE RESEARCH

This research is significant in four aspects. It gains importance because four different but significant objectives are considered which improves the power system network operation in a cost effective manner. Secondly, this research demonstrates the effectiveness of MOPSO and MOCLPSO as tools for obtaining efficient pareto optimal solutions for the optimal TCSC placement problem. This research is significant especially in considering MOCLPSO, a variant of MOPSO among the growing number of variants for validating its effectiveness in solving this problem. Next, this research is significant as it uses a methodology for finding the limiting minimum and maximum number of TCSCs to be installed in a power system. Finally, it is also significant particularly in applying two popular MCDM techniques in aiding the decision maker to choose a single trade off solution which is otherwise a challenging task.
1.6 LITERATURE SURVEY

Many researches were made on the optimal allocation of FACTS devices and several techniques have been applied for finding the same. According to the characteristics of FACTS devices, various criteria have been considered in the above mentioned allocation problem. Some of the optimization objectives considered in the literature are given below.

1.6.1 Loss Minimization

The various literature considering loss minimization as an objective for the placement of FACTS devices are discussed below.

Preedavichit and Srivastava (1997) considered the settings of FACTS devices as additional control parameters in the optimal reactive power dispatch formulation and studied the impact on system loss minimization. Static models of three FACTS devices consisting of SVC, TCSC and Thyristor Controlled Phase Angle Regulator (TCPAR) were included in the optimal reactive power dispatch formulations. The results of optimal reactive power dispatch were obtained on a practical network of Electricity Generating Authority of Thailand.

Abdel-Moamen and Padhy (2003) developed and analyzed an optimal power flow (OPF) model with TCSC for practical power networks using Newton's optimization technique. Here, the minimization of total system real power loss was an objective while controlling the power flow of specified transmission lines. This model had considered the different optimal settings of the generators, transformers and TCSC devices. The optimal transmission losses and the corresponding generation schedules with optimal TCSC parameter settings for different case studies were also reported. The
performance of the proposed algorithm was tested on the IEEE 30-bus system with single and multiple TCSC devices.

Chettih et al. (2008) presented a Genetic Algorithm (GA) approach for solving the reactive power flow problem including the line flow constraint. Minimizations of real power loss with FACTS devices and without FACTS devices were the objectives of this reactive power optimization problem. The proposed method was successfully applied in the case of a Western Algerian transmission system. The FACTS placement problem in their study considered the upper and lower bound constraints of voltage at different load levels by minimizing the system loss.

1.6.2 Single Objective Loadability Maximization

Many of the previous researches have considered the optimal allocation of FACTS devices for loadability maximization of the transmission systems. Among them, most of the researches have concentrated on finding a single optimal solution for the loadability problem even though the actual requirement of most systems requires multi-objective optimization.

Kobayashi et al. (1997) proposed a two-step procedure to locate and adjust Thyristor controlled phase shifter transformers’ (TCPST) angles. In the first step, the theoretical system maximum loadability was found without restrictions on number and location of the control devices. In the second step, this ideal loadability was maintained while minimizing the system-wide installed TCPSTs’ capacity. The assumption was that every line in a system had an installed TCPST whose setting was optimally adjusted within the line flow limits.

Gerbex et al. (2001) applied GA to optimize the location, type and ratings of multi-type FACTS devices for maximizing the loadability of the
Four different kinds of FACTS devices namely TCSC, TCPST, Thyristor controlled voltage regulator (TCVR) and SVC were used. Here, the FACTS devices were modeled for steady-state studies. Simulations were done on a 118-bus power system for several number of devices. A maximum number of FACTS devices beyond which the loadability of the system could not be improved was observed.

Mixed Integer Linear Programming (MILP) was applied by Lima et al. (2002) for finding the number, location and the settings of TCPSTs to maximize the system loadability. The procedure minimized one of the two objective functions which are total generation cost and system loadability. The method accounted for DC load flow equations, line flow limits, generation limits and TCPST constraints. Simulations were done for a modified IEEE 24-bus network.

Hao et al. (2004) presented a mathematical model for the optimal location and the parameters of UPFCs to maximise the system loadability subject to the transmission line capacity limits and specified voltage level. Self-adaptive evolutionary programming was used to solve the non-linear programming problem for better accuracy. Case studies of the IEEE 30-bus and IEEE 118-bus systems using the proposed model and technique demonstrate that the proposed mathematical model is efficient.

Kazemi and Badrzadeh (2004) applied bifurcation analysis to find the optimal location and ratings of SVC and TCSC and used a Continuation Power Flow (CPF) to evaluate the effects of these devices on system loadability. Eigen vector analysis was applied at the maximum loading point to rank the most critical voltage buses. After this, it was possible to optimize the location, sizing and control modes of SVC and TCSC in order to achieve maximum enhancement of system loadability. The models and methodology
for placing and designing SVC and TCSC were tested in a 173 bus AC/DC system.

Sharma et al. (2005) proposed a new methodology for combined location of TCPAR and TCSC using a MILP approach in the deregulated electricity environment. The methodology was based on DC load flow equations with constraints on generation, line flow, TCPAR and TCSC parameters, power angle, and number of FACTS controllers. The system loadability was determined without and with the combined optimal location of FACTS controllers for a pool model and a hybrid model using secure bilateral transaction matrix. The results were compared for a pool model and a hybrid model with and without the optimal location of FACTS controllers. The proposed technique was demonstrated on IEEE 24-bus reliability test system.

Singh and Erlich (2005) used UPFC to enhance the system loadability. A method to determine the suitable location of UPFC was suggested based on the sensitivity of system loading with respect to the control parameters of the UPFC. An OPF was formulated and was used to maximize system loadability subject to the power balance equations, system operating and UPFC parameters constraints. The effectiveness of the proposed algorithm was tested and illustrated on 5-bus and IEEE 14-bus systems. Test results obtained on the test systems show that the new sensitivity factors suggested by them could be effectively used for increasing the loadability of the system with UPFC.

Singh et al. (2006) suggested a new sensitivity based approach to locate TCSC and UPFC in the transmission system for enhancing the power system loadability. The effectiveness of the proposed method was tested and illustrated on 5-bus and IEEE 14-bus systems.
A methodology based on an evolutionary algorithm known as Evolution Strategies for optimally locating FACTS controllers in a power system for system loadability maximization was presented by Santiago-Luna and Cedeno-Maldonado (2006). Three important aspects considered in the optimization were the types of FACTS devices used, their location and their settings. Simulations were carried out on a modified IEEE 30-bus test system. The results obtained demonstrate that the best option to increase the loadability of the system is by using different types of FACTS devices simultaneously. In all the case studies considered, they found that there was a maximum number of FACTS devices that could be used, beyond which the system loadability did not increase any further.

Karystianos et al. (2007) examined the problem of maximizing power-system loadability with multiple constraints representing generator limits. The structure of the loadability surface was investigated and the various types of limits were classified. A general algorithm to optimize the settings of control variables in order to maximize the loadability margin was developed. The importance of non-smooth corner points of the loadability surface was discussed. At such limits, maximization of loadability margin was performed based on techniques provided by non-linear optimization theory. For this purpose, an algorithm to identify multiple binding constraints on a corner point was developed. Illustrative examples on small, but realistic systems were included.

Parastar et al. (2007) used modified particle swarm optimization (PSO) to optimize the various process parameters of FACTS devices in a power system. The various parameters taken into consideration were the location of the devices, their type, and their ratings. The simulation was performed on a modified IEEE 30-bus power system with two types of FACTS controllers namely SVC and TCSC, modeled for steady state studies.
The optimization results clearly indicate that the introduction of FACTS devices in a right location increases the loadability of the system and the algorithm can be effectively used for this kind of optimization.

Minguez et al. (2007) addressed the optimal placement of SVCs in a transmission network for maximizing its loading margin. A multi scenario framework including contingencies was considered. This problem was formulated as a non-linear programming problem including binary decisions which are the variables to decide the actual placement of the SVCs. Here, a Benders decomposition technique within a restart framework was used. Detailed numerical simulations on realistic electric energy systems demonstrate the appropriate behavior of the proposed technique.

Chang and Chang (2009) used CPF technique to maximize the transmission loadability from the peak load through installation of SVCs and TCSCs. Three main steps in the FACTS devices installation strategy were proposed. In step 1, based on the peak-load state, the CPF technique was used to formulate the maximum transmission loadability (MTL) problem through installation of the FACTS devices. In step 2, based on the power flow solution for the MTL obtained in step 1, the positions appropriate to place SVCs and TCSCs were determined using the tangent vector technique and real power flow performance index sensitivity factors, respectively. Various FACTS devices installation schemes were then built with these candidate positions and, for each scheme, the MTL was solved by determining the ratings for the SVCs and TCSCs installed. Finally in step 3, by comparing the ratios of the investment costs to the increase in transmission loadability obtained in the various schemes, the most advantageous scheme was suggested.

A survey of several technical literature related to the enhancement of loadability of power system networks is presented by Bindeshwar et al. (2010). Here, a comprehensive review of various methods for incorporation of
differential algebraic equations model of FACTS controllers and different types of load models in large-scale emerging power systems for their loadability enhancement is presented.

1.6.3 Multiple Objectives Including Loadability Maximization

Researches concentrating on multiple objectives for the loadability maximization problem using FACTS devices are limited. Most of them are oriented towards technical and economical concerns. For dealing with multiple objectives together, several methods were proposed in previous literatures and are discussed in this section.

1.6.3.1 Loadability Maximization and Minimizing the Cost of FACTS Devices as Objectives

A few researches have considered the cost of installation of FACTS devices along with loadability maximization.

Lima et al. (2003) conducted a preliminary design study on the combinatorial optimal placement of TCPSTs in large-scale power systems using the advancements in MILP. They found the number, location, and settings of phase shifters to maximize system loadability under the DC load flow model, subject to the limits on the installation investment or total number of TCPSTs. Active power flow limits, generation limits, and phase shifter constraints were also accounted. Simulation results were presented for the IEEE 24-bus system, IEEE 118-bus system, IEEE 300-bus system, and a 904-bus network. The principal characteristics of their approach were compared with the other FACTS allocation methods available in the literature.
Shaheen et al. (2007) discussed the application of two evolutionary optimization techniques, namely GA and PSO to find out the optimal number, the optimal location, and the optimal parameters of multiple UPFC devices. These variables were optimized to maximize the system loadability with minimum installation cost of UPFC devices. Simulations were performed on IEEE 6-bus power system and IEEE 14-bus power system to show the validity of the applied techniques and for comparison purposes. The results obtained show that UPFC can significantly increase the system loadability. The results also indicate that both the techniques can successfully find out the optimal location and the optimal parameters of multiple UPFCs.

Saravanan et al. (2007) have presented the application of PSO technique to find the optimal location of three types of FACTS devices namely TCSC, SVC and UPFC for enhancing the system loadability with minimum cost of installation of FACTS devices. While finding the optimal location, thermal limit for the lines and voltage limit for the buses were taken as constraints. Simulations were performed on IEEE 6, 30 and 118-bus systems and on the Tamil Nadu Electricity Board 69 bus system.

Rashed et al. (2007) have presented the application of GA and PSO techniques for finding out the optimal number, location, and parameter settings of multiple TCSC devices to achieve maximum system loadability with minimum installation cost of TCSCs. The thermal limits of the lines and the voltage limits for the buses were taken as constraints for the optimization process. Simulations were performed on IEEE 6-bus and IEEE 14-bus power systems. The results show that TCSC is one of the most effective series compensation devices that can significantly increase the system loadability. The results also indicate that both GA and PSO techniques can easily and successfully find out the optimal variables, but PSO is faster than GA from the time perspective.
1.6.3.2 Loadability Maximization and Loss Minimization as Objectives

Researches dealing with loadability maximization and loss minimization are presented in this section.

Mahdad et al. (2006), focused on the types of FACTS devices to be installed and their location in a power system. They proposed an approach using heuristic and practical rules for the optimal location of two types of FACTS devices namely, SVC and TCSC. Here the system loadability and loss minimization were taken as the measures of power system performance and a 9-bus system was used for testing. Results show the impact of optimal operating points of SVC and TCSC on the system under various conditions of a power system.

Vijayapriya et al. (2010) focused on the optimal placement of UPFC for increasing the stability of a system, maximizing the system loadability and minimizing the losses in the network. The analyses used were Small Signal Stability, Time Domain Analysis and Power Flow which were performed using Power System Analysis Toolbox (PSAT). By placing UPFC in a particular line connected to the most critical bus, losses were minimized, loadability was increased and stability was maintained.

1.6.3.3 Other Objectives

The other objectives such as generation cost minimization, enhancement of Available Transfer Capability (ATC) and increasing the security margin, which are presented in the existing literature are discussed in this section.

Galiana et al. (1996) used the concept of security regions to systematically and objectively compare the impact of various FACTS devices
on the behavior of power systems. Scalar measures of the steady-state performance of a power system with FACTS devices were used to quantify this impact. Such measures were obtained by solving an OPF within the constraints of the security region. The concept of the ideal FACTS device was introduced as a means to establish a theoretical upper bound on the performance of any realizable FACTS device. This ideal FACTS device was tested and compared against non-ideal FACTS device including the variable series reactance and the variable phase-shifter. Simulations were done on the IEEE 30 and 118-bus networks to illustrate the above concepts.

The improvement in the system loadability and the cost of power production were discussed by Paterni et al. (1999). They proposed an index for measuring the benefits of a given set of TCPSTs. The best location for a set of TCPSTs was found by GA for a 36 line test case and for a French network.

Mohamad Idris et al. (2009) used a novel algorithm known as multi-objective bees algorithm for the optimal allocation of FACTS devices in a restructured power system to enhance the ATC of power transactions between source and sink areas and minimize the overall system cost comprising of the investments costs on FACTS devices and generation cost. This problem was formulated as a multi-objective optimization problem. Three types of FACTS namely TCSC, SVC and TCPST were used in this study. A Non-dominated Sorting GA-II (NSGA-II) technique was used and validated on IEEE 30-bus system.

Gitizadeh and Kalantar (2009) presented a novel approach to find the optimal location, type, and capacity of FACTS devices in a power system using a multi-objective optimization function. TCSC and SVC were utilized to achieve the objectives of active power loss reduction, cost reduction of newly introduced FACTS devices, increasing the robustness of the security
margin against voltage collapse and voltage deviation reduction. The operational and controlling constraints as well as load constraints were considered in the optimum allocation procedure. A goal attainment method based on simulated annealing (SA) was used to approach the global optimum. In addition, the estimated annual load profile was utilized for the optimal location of FACTS devices to approach a practical solution. The standard IEEE 14-bus test system was used to validate the performance and effectiveness of the proposed method.

1.6.4 Loadability Calculation

As one of the important focal points of this research is loadability enhancement of transmission system, it is essential to have an understanding of the computational methods of loadability.

Earlier researches have suggested procedures to compute loadability of a transmission system. For assessing transmission system loadability, a procedure was proposed which expressed loadability in terms of a percentage loading of system buses. Klump and Overbye (1997) expressed loadability in terms of a percentage loading of power system buses and in order to quantify system loadability, they expressed loadability as the degree to which the transmission system could serve the additional load in terms of percent loading estimate. The loading condition of a system was increased by multiplying the base loading condition by a multiplier called the loading factor under the condition that, all loads contributed to the system loadability. Consequently, the transmission system loadability was expressed in terms of the loading factor.

On the same note, Gerbex et al. (2001) increased all loads and real power generation in the same proportion and the additional losses due to the
increase in power transmission were shared out among all the generators in proportion to their generated power.

Rashed et al. (2007) adjusted both real and reactive powers of load along with real power generation uniformly for loadability calculation.

Saravanan et al. (2007) and Minguez et al. (2007) considered uniform increase of real power at all the load buses for loadability calculation and the increase in load was met by the slack bus.

Rosero and Rios (2007) increased real power load and generation in the same proportion and a single slack bus model was used.

Singh and Erlich (2005) considered uniform loading with the same power factor at all the load buses and the increase in loading was assumed to be taken care of by the slack bus. Modi, et al. (2008) also followed the same procedure for loadability calculation.

1.6.5 Multi-Objective Optimization Techniques

A number of modern multi-objective optimization techniques are presented in literature for solving multi-objective optimization problems as sampled in (Deb 2001). MOPSO and its variants are one among those techniques that are used on a variety of engineering applications with great success. MOCLPSO, one of the variants of MOPSO is also popular. Recently, MOPSO techniques have received added attention for their application in power system problems for the placement of FACTS devices (Benabid et al. 2009). MOPSO is an extension of PSO algorithm to handle multi-objective optimization problems (Coello and Lechuga 2002). MOCLPSO is a simple, effective and stable multi-objective evolutionary algorithm proposed by Huang et al. (2006). Venayagamoorthy and Harley (2007) highlighted the
application of swarm intelligence techniques for solving some of the transmission system control problems.

### 1.6.5.1 Applications of MOPSO for Multi-Objective Optimization Problems

A MOPSO approach for multi-objective economic load dispatch problem in power system was presented by Bo Zhao and Yi-jia Cao (2005). The problem was handled as a multi-objective problem with competing and non-commensurable objectives such as minimization of fuel cost, emission and system loss. MOPSO was incorporated with a diversity-preserving mechanism by using an external memory called repository and it used a geographically-based approach to find a widely different pareto optimal solutions.

Hongwen Yan and Rui Ma (2006) presented a new approach for environmental/economic transaction planning problem in the electricity market. The environmental/economic transaction planning problem was formulated as a multi-objective optimal power flow (MOPF) problem. A novel algorithm using MOPSO and non-stationary, multi-stage assignment penalty function was proposed to solve this problem.

Mollazei et al. (2007) used MOPSO algorithm to find the optimal location of TCSC and its parameter in order to increase total transfer capability, reduce total transmission losses and reduce voltage deviation. This multi-objective optimization problem was solved using the MOPSO with sigma method and encouraging results were obtained.

Hazra and Sinha (2007) presented an effective method of congestion management in power systems. The two conflicting objectives namely reduction of overload and minimization of cost of operation were
optimized to provide pareto optimal solutions. A MOPSO method was used to solve this complex, non-linear optimization problem. A realistic frequency and voltage dependent load flow method which considered the voltage and frequency dependence of loads and generator regulation characteristics was used to solve this problem. The proposed algorithm was tested on IEEE 30-bus system, IEEE 118-bus system, and Northern Region Electricity Board India (NREB) 390-bus system with smooth as well as non-smooth cost functions due to valve point loading effect.

Mehdi Eghbal et al. (2008) presented an evolutionary multi-objective optimization approach to find the optimal solution of VAR expansion and ATC enhancement problems. The problem was formulated as a non-linear, constrained multi-objective optimization problem. The aim was to obtain an optimal allocation of FACTS devices that was optimal in terms of minimizing the total cost of the VAR expansion problem and maximizing the amount of ATC. A MOPSO approach based on pareto optimality was proposed to find a set of possible optimal solutions. The proposed approach was successfully tested on IEEE 14-bus test system.

Krishna Teerth Chaturvedi et al. (2008) proposed MOPSO for solving the environmental/ economic dispatch (EED) problem. The problem was formulated as a non-linear, constrained multi-objective optimization problem with equality and inequality constraints for simultaneous minimization of cost and emission content. Fuzzy membership function was used to find the best compromise solution out of the available pareto optimal solutions.

Sharaf and El-Gammal (2009) presented a novel technique for capacitor sizing using the multi-objective, multi-stage PSO to determine the optimal capacitor sizes in a radial distribution system. The main objective functions were to minimize the feeder current for feeder loss reduction,
voltage deviation at each bus of the distribution system and feeder capacity release.

Abido (2009) proposed a new MOPSO technique for EED problem. The proposed MOPSO technique was implemented to solve the EED problem with competing and non-commensurable cost and emission objectives. Several optimization runs of the proposed approach were carried out on a standard test system. The results demonstrate the capability of the proposed MOPSO technique to generate a set of well-distributed pareto optimal solutions in one single run.

Hazra and Sinha (2011) presented a MOPF technique using PSO. Two conflicting objectives such as generation cost, and environmental pollution were minimized simultaneously. A MOPSO method was used to solve this highly non-linear and non-convex optimization problem. A diversity preserving technique was incorporated to generate evenly distributed pareto optimal solutions. A fuzzy membership function was proposed to choose a compromise solution from the set of pareto optimal solutions. The algorithm was tested on IEEE 30 and 118-bus systems and its effectiveness was illustrated.

### 1.6.5.2 MOCLPSO and its Applications

Huang et al. (2006) presented an approach to integrate a pareto dominance concept into a Comprehensive Learning Particle Swarm Optimizer (CLPSO) to handle multiple objective optimization problems. They also integrated an external archive technique with MOCLPSO. Simulation results on six test problems showed that the proposed MOCLPSO, for most problems, was able to find a much better spread of solutions and faster convergence to the true pareto optimal front compared to two other multi-objective optimization evolutionary algorithms.
Victoire and Suganthan (2007) proposed a MOCLPSO approach for multi-objective EED problem in electric power system. The proposed MOCLPSO approach handled the problem with competing and non-commensurable objectives of fuel cost and emission. MOCLPSO adopted a diversity-preserving mechanism using an external memory called repository and pareto dominance concept to find widely different pareto optimal solutions. Simulations were conducted on typical power system problems. The superiority of the algorithm in converging to a better pareto optimal front with fewer fitness function evaluations was exhibited.

1.7 MCDM

In multi-objective optimization problems, choosing a unique solution from multiple outcomes is a challenging issue and has received a lukewarm attention so far. Therefore, meaningful research has to be done to support the decision-maker during the post-pareto analysis phase. To help the decision maker in choosing a single solution, there exists a wide variety of MCDM techniques in literature. Out of these, TOPSIS and FCM clustering are popular. TOPSIS was proposed by Hwang and Yoon (1981) to solve classical MCDM problems. This method uses numerical values to indicate the objective function preferences. This is a simple method that yields efficient results for any decision maker who can prioritize the objective functions to find appropriate solutions. The second method is FCM clustering technique. One of the most efficient clustering methodologies is fuzzy clustering and a widely used fuzzy clustering method is the FCM clustering algorithm. FCM clustering was introduced by Bezdek (1973).

1.7.1 Applications of TOPSIS for MCDM Problems

TOPSIS finds its application to a great extent in the literature.
Avinandan Mukherjee and Prithwiraj Nath (2005) proposed and assessed three comparative approaches namely modified gap model, TOPSIS and loss function to measure service quality. The empirical data on service quality was collected from a large sample of consumers of leading Indian commercial banks. The service quality evaluations calculated from the three distinct methods were compared and tested for their mutual agreement.

Tien-Chin Wang et al. (2006) employed TOPSIS to select the most suitable candidate as surveyor among many candidates. They demonstrated the application of TOPSIS method as one of the best methods for selecting a suitable candidate. The approach was based on a two-step procedure. The study was conducted using the data from an illustrative example provided by ABC shipping company and the proposed method was applied to select the most suitable surveyor among five candidates in February 2005.

Javad Dodangeh et al. (2010) demonstrated a model for selection and ranking of strategic plans in balanced score card using TOPSIS method and Goal Programming model. The balanced score card’s objectives and perspectives were arrived with the opinions and consensus of organization’s managers and experts. The choice of strategic plans for implementation in the balanced score card was selected using Goal Programming model and TOPSIS method. The results reveal that these methods are more reliable and acceptable.

Azzam and Mousa (2010) presented a new approach based on the combination of GA and the ε-dominance concept to solve the multi-objective reactive power compensation problem. The algorithm maintained a finite-sized archive of non-dominated solutions. Moreover to help the decision maker to extract the best compromise solution from a finite set of alternatives, TOPSIS method was adopted. The proposed approach was carried out on the standard IEEE 30-bus test system. The results demonstrate the capability of
the proposed approach to generate true and well distributed pareto optimal solutions for the multi-objective reactive power compensation problem in one single run.

1.7.2 Applications of FCM Clustering for MCDM Problems

Applications based on FCM clustering are proposed in several papers. Panigrahi et al. (2006) presented a new approach to distinguish between inrush current and internal faults of power transformer using pattern recognition approach. Hyperbolic S-transform was used to extract patterns of inrush current and internal faults from the captured transformer current. The spectral energy and standard deviation were calculated to distinguish between inrush current and internal fault. Classification of internal faults and inrush current was done through FCM clustering.

Guo Xian Tan et al. (2008) proposed a method to extract writer information at the character level from online handwritten documents for indexing and retrieval of the documents. The method did not place any constraints on the content being written or writing styles of the writers. A FCM clustering approach was presented to cluster and classify the character prototypes for writer identification. The proposed system attained an accuracy of 97.6% on 82 writers and an accuracy of 98.3% when retrieved from a scaled up larger database of 120 writers.

Prahastono et al. (2008) concentrated on the FCM clustering classification method for clustering electricity load profiles that could belong to more than one group at the same time. The simulation of FCM clustering was carried out using actual sample data from Indonesia and the results were presented. Some validity index measurements were carried out to estimate the compactness of the resulting clusters or to find the optimal number of clusters for a data set.
Khatami et al. (2009) developed a linearized Heffron-Philips model of a single-machine infinite-bus power system with a TCSC controller to damp low frequency oscillations effectively. They designed the TCSC controller based on FCM clustering which adjusted the control signal by appropriately processing the input signals and provided an efficient damping. The results of the simulation show that TCSC with FCM clustering controller is more effective in damping low frequency oscillations compared to TCSC with lead-lag compensator.

Chu XiaoLi et al. (2010) proposed a method of image segmentation based on FCM clustering algorithm and Artificial Fish Swarm Algorithm. The image was segmented in terms of the membership values of the pixels. Artificial Fish Swarm Algorithm was introduced into FCM clustering algorithm and the optimised clustering center was selected adaptively. The experimental results show the effectiveness and feasibility.

1.8 RESEARCH GAP IDENTIFIED FROM LITERATURE SURVEY

From the aforementioned literature review the following findings are observed. Several methods for optimal allocation of FACTS devices to maximize the loadability of a system were proposed in the literature but an integrated approach to simultaneously find the optimal solution considering the aforesaid objective functions has not been reported. Generally in the multi-objective power system problems, the bi-objective case is the most heavily studied. A multi-objective optimization problem with more than three objectives is a special case of multi-objective problems that needs further investigation. This research aims at covering this gap by extending the problem of optimal placement of TCSCs to handle four objectives simultaneously. This investigation attempts to improve upon the previously mentioned researches in the field of optimal placement of FACTS devices in
power systems by simultaneously considering multiple objectives such as transmission system loadability enhancement, transmission loss reduction, TCSC installation cost reduction and reduction in load bus voltage deviation. The utilized FACTS device for optimization is TCSC.

1.9 OBJECTIVES OF THE RESEARCH

Finding the optimum solution to simultaneously optimize all the objectives in a FACTS devices allocation problem is really vital for the present power systems, and therefore, it is worth spending more time on such an important decision. After identification through an extensive literature study, the following objectives have been outlined for this research work. To demonstrate the importance of all the objectives, optimization is performed by considering two objectives initially and then increasing the number of objectives to three and four subsequently. The specific objectives of this research are:

- To optimally place TCSCs in a power system for maximizing the loadability of transmission lines and minimizing the transmission loss.

- To optimally place TCSCs in a power system for maximizing the loadability of transmission lines, minimizing the transmission loss and minimizing the cost of TCSCs.

- To optimally place TCSCs in a power system for maximizing the loadability of transmission lines, minimizing the transmission loss, minimizing the cost of TCSCs and minimizing the voltage deviation at the load buses.

- To analyse the effect of increasing the number of objectives and to compare the results obtained for all the three cases.
• To compare the results obtained from the implementation of MOPSO and MOCLPSO techniques for determining the optimal location and parameters of TCSCs for the above mentioned objectives.

• To obtain the true pareto front by weighted sum method using CLPSO and to compare it with MOPSO and MOCLPSO.

• To employ TOPSIS and FCM clustering in the post-pareto analysis phase to reduce the set of all non-dominated solutions to a manageable number.

1.10 OUTLINE OF THE THESIS

The thesis is organized as follows. A detailed review on the literatures regarding the researches which have been carried out related to this research is presented in the first chapter. The primary objectives of the thesis are also discussed in depth in the first chapter.

The second chapter gives a brief background on the multi-objective optimization techniques employed and the MCDM techniques used in this thesis. An introduction to multi-objective optimization is given in this chapter and it is followed by an overview of multi-objective optimization techniques namely MOPSO and MOCLPSO which are used in this research. The fundamentals of each optimization method are presented in this overview. The second chapter also gives a brief overview of the classical weighted sum method for solving the multi-objective optimization problem. This chapter also describes the two MCDM techniques, TOPSIS and FCM clustering which are employed in this research. Moreover, the second chapter explains the methodology proposed for solving the multi-objective optimization problem discussed in this research.
The third chapter describes the multi-objective optimization of loadability of transmission system and transmission loss by optimally placing the TCSCs and the results obtained are detailed. Problem formulation section describing the loadability enhancement problem and the loss minimization problem is also included in the third chapter. MOPSO and MOCLPSO are applied for finding the optimal location and ratings of TCSCs. The computational results of the MOPSO and MOCLPSO on the test systems, as well as their comparison with the classical weighted sum approach for the bi-objective optimization problem reported in this chapter are provided at the end of this chapter.

The fourth chapter elaborates the multi-objective optimization for the optimal placement of TCSCs with three objectives including the cost of TCSCs along with the two objectives mentioned in the previous chapter. MOPSO, MOCLPSO and weighted sum method are tested and compared, and the results are discussed.

The fifth chapter enumerates the multi-objective optimization of the loadability of transmission lines, the transmission loss, the cost of TCSCs and the voltage deviation at the load buses. In this chapter, an enhancement to the optimization problem presented in the previous chapter is done by including one more objective of minimizing the voltage deviation at the load buses and presents simulation results, statistical analysis and comparison between methods.

Finally, in the sixth chapter, conclusions, contributions of this research, future work directions and suggestions are presented. The findings from this research are also discussed. Additionally, appendix 1 and appendix 2 present a complete database of IEEE 14-bus and IEEE 118-bus systems respectively.
1.11 SUMMARY

In the present power market scenario, utilizing the maximum transmission capability of transmission lines is a very important aspect due to the fast growing power demand. Transmission system performance can be enhanced by utilizing FACTS devices. Among the various FACTS devices, TCSC is considered in this research. A novel methodology for finding the limiting minimum and maximum number of TCSCs to be installed in a power system is proposed and implemented in this thesis. The optimization of transmission system performance can be accomplished by increasing the power transmission capability, reducing the power loss, improving the voltage profile and others.

In this research, a multi-objective optimization problem is formulated for the optimal placement of TCSCs with the objectives of simultaneously maximizing transmission system loadability and minimizing the factors, transmission loss, cost of TCSCs and voltage deviation at the load buses. The impact of each objective is studied by considering three combinations of these objectives. This thesis presents a novel approach to find the optimal location and parameters of TCSCs in transmission systems using multi-objective optimization techniques. Two swarm intelligence based multi-objective techniques, namely MOPSO and MOCLPSO are applied for arriving at the pareto optimal solutions to this non-linear, multi-objective TCSC placement problem. The results obtained are compared with the classical weighted sum method, solved using CLPSO.

In this research, two novel MCDM methods are proposed for obtaining the final solution from the set of pareto optimal solutions. The power system planner can make use of these non-dominated solutions as per his/her own convenience for optimum performance of respective objective functions. The developed methods in this research can guide the power system planners in efficient utilization of the existing transmission systems.