Allocating TCSC for Transmission Congestion Management in Deregulated Environment

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Submitted By

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Declaration

I hereby certify that the work which is presented in dissertation entitled, "**Allocating TCSC for Transmission Congestion Management in Deregulated Environment**", in partial fulfillment of the requirements for the award of the degree of **Master of Engineering** in **Power Systems**, submitted to Electrical & Instrumentation Engineering Department of Thapar University, Patiala is as authentic record of my own work carried under the supervision of **Dr. Sanjay K. Jain**. It refers others researchers work which are duly listed in the reference section. The matter contained in this dissertation has not been submitted, neither in part nor in full to any other degree to any other university or institute except as reported in text and references.

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It is certified that the above statement made by the student is correct to the best of my knowledge and belief.

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Abstract

Congestion management is an essential aspect in the restructured power market. The key objective is to alleviate or reduce the congestion from the lines for the consistent and economic operation of the system. There are different ways to manage congestion such as cost-free approach and non-cost free approach. In this dissertation, cost-free approach i.e., use of FACTS devices has been employed to overcome the congestion problem. Two methods, namely LMP difference method and congestion rent contribution method have been used for installing the series FACTS device in the most optimal place. These methods depend on nodal prices which are obtained from the optimal power flow solution. Hence, these have been obtained from DC optimal power flow in the presented work. The techniques used for this purpose are- linear programming (LP) and genetic algorithm (GA). The comparison has been made between both the techniques on the basis of generation cost and LMP values. It has been found that generation re-dispatch with GA leads to savings in the generation cost. Hence, GA technique has been used to find the most optimum location to allocate TCSC which gives the minimum congestion rent value. In order to show the efficacy of the employed methods, they have been applied on two IEEE test systems.

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List of Symbols

P_j	Active power injection at bus j
θ	Angle of bus voltage
$B_j(P_{D_j})$	Benefit curve for j^{th} demand
$C_j(P_{G_j})$	Bid curve of j^{th} generator
LMP_j^{cong}	Congestion component of LMP at bus j
CCC_{jk}	Congestion rent contribution of line $j-k$
CC_{jk}	Congestion rent of line $j-k$
μ_m	Constraint cost of line m
DF_j	Delivery factor at bus j
DF_j^{est}	Delivery factor from prior iteration at bus j
P_{D_j}	Demand at bus j
E_j	FND at bus j
P_{G_j}	Generation at bus j
C_j	Generation cost at bus j
$GSF_{m,j}$	Generation shift factor of line m at bus j
B_{jk}	Inverse of reactance between buses j and k
f	Linear objective function i.e. cost function
LMP_j	LMP at bus j
LMP_{jk}	Locational marginal price difference between buses j & k
LMP_j^{loss}	Loss component of LMP at bus j
LF_j	Loss factor at bus j
Aeq	Matrix for linear equality constraints
A	Matrix of linear inequality constraints
$P_{G_j}^{max}, P_{G_j}^{min}$	Max. and min. generation output at bus j
n_b	Number of buses
n_g	Number of generators
K	Number of lines
n_d	Number of loads
P_{jk}	Power flow across line $j-k$
F_m	Power flow of line m
$P_{F,j}$	Power injection at node j due to TCSC installation
$P_{F,k}$	Power injection at node k due to TCSC installation

λ	Price at the slack bus
X_L	Reactance of line
R_m	Resistance of line m
$limit_m$	Thermal limit of line m
P_{Loss}	Total loss
beq	Vector for linear equality constraints
b	Vector of linear inequality constraints
lb	Vector of lower limits of generation
ub	Vector of upper limits of generation

List of Abbreviations

ACOPF	AC optimal power flow
ATC	Available transfer capacity
DCOPF	DC optimal power flow
DISCO	Distribution company
EAI	Energy automation and information
FACTS	Flexible alternating current transmission system
FND	Fictitious nodal demand
GA	Genetic algorithm
GENCO	Generation company
ISO	Independent system operator
LMP	Locational marginal price
LP	Linear programming
NYISO	New York independent system operator
TCC	Total congestion rent
TCSC	Thyristor controlled series compensator
UPFC	Unified power flow controller

Chapter 1

Introduction

1.1 Overview

Restructuring of the power sector, commonly known as deregulation, refers to unbundling the originally vertically integrated system into three different businesses i.e., generation, transmission and distribution as shown in Figure 1.1. There should be a great number of market participants for effective competition. Hence, generation and distribution businesses are vertically cut and horizontally separated as shown in Figure 1.2.

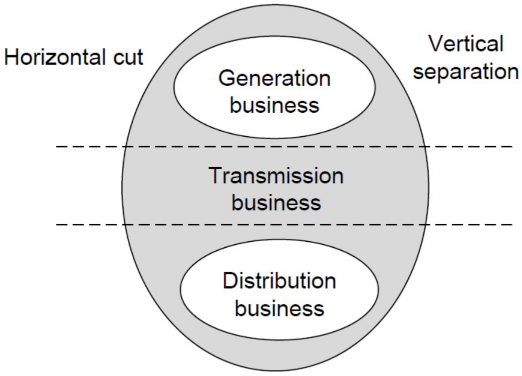

Figure 1.1: Vertically integrated power market

Deregulation aims at offering competition in generation and distribution businesses. The decision of generation investments is now under the private entities [1]. The presence of mismanage-

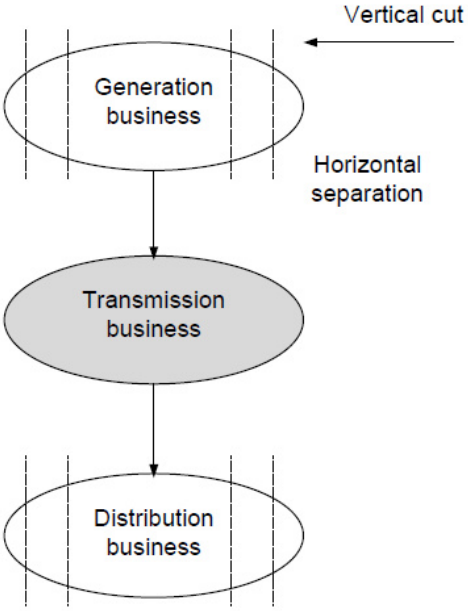

Figure 1.2: Vertically unbundled power market

ment between generation and transmission investments and the condition of the bilateral contracts (over the counter) which do not occur on regulated exchanges, permits the generation company (GENCO) and distribution company (DISCO) to confer power transactions autonomously. Such transactions are not being provided by a transmission system because of its limited capacity and security issues. So, this may result in transmission congestion in the network.

Congestion is the most elementary transmission management concern. It is a condition when owing to unpredicted contingencies there is inadequate transmission capability to employ every dealt transaction at the same time. It may be reduced by scheduling and including line flow constraints in the generation dispatch. This includes generation re-dispatch and load shedding. Other ways are the operation of FACTS devices or phase-shifters [2]. FACTS device like thyristor controlled series compensator (TCSC) may be used for managing congestion. This device controls the reactance in the transmission line and helps in managing the line flows in overloaded transmission lines.

Two methods are employed to place FACTS device in the most optimal location namely, LMP difference method and congestion rent contribution method. Both the methods depend on upon LMPs or nodal prices. Linear programming (LP) technique and genetic algorithm (GA) technique can be used to compute LMPs at every bus while minimizing the total generation cost (objective function). The re-dispatch of generation by GA technique results in significant savings in the generation cost in comparison to the LP technique.

1.2 Literature Review

Restructuring of the power system is anticipated to propose an extensive range of benefits to the consumers. It offers advantages like lesser electricity price, enhanced customer service, and improved efficiency of the system. Venkatesh *et al.* [1], gave a detailed description of deregulation, Indian power scenario, operations of the power market, challenges in a competitive environment like available transfer capacity (ATC) and transmission pricing. Shahidehpour *et al.* [2], discussed the electric power system market operations. A complete outline of post-deregulation market operations in electrical power systems has been explained. Stoft [3], described the transmission investment in a deregulated electricity market. The concept of transmission planning, transmission rights and transmission monopolies have been adequately illustrated.

The unbundling of the vertically integrated system leads to several technical concerns. Basic challenges are to ensure secure, economical and stable operation of the system. These issues have to be tackled carefully in the restructured power market. The investment decision is under the private entities and the provision of bilateral transactions is also present. Blanco *et al.* [4], described the flexible investment decisions in the interconnected transmission system. An approach in which stochastic simulations include uncertainties like the development of fuel costs and demand growth has been presented. Every party aims to achieve the advantage from cheaper generating sources which might lead to congestion in the transmission line. Some parties try to realize market power by exploitation of the system limits. Thus, there is a need to manage the transmission network for reliable and secured operation. This is managed by the system operator while ensuring open access to all participants of the market. So, congestion management is quite an essential aspect in the deregulated market. Srivastava *et al.* [5], proposed a new approach for calculation of transmission pricing taking social welfare maximization as the objective. The details about the transmission and dispatching operations with respect to the New York independent system operator (NYISO) are summarized in the manual [6].

There are different ways to overcome congestion namely, cost-free and non-cost free methods. Among cost-free methods, FACTS device installation is the most employed one. It can be located using the marginal prices technique by determining the most optimal location. The website [7], gave a detailed description of restructured power system and calculation of locational marginal prices. Christie and Wollenberg [8], discussed the congestion-management issues and three different methods for managing the transmission system operation. Singh and Verma [9], proposed congestion management using the optimal power flow (OPF) technique. The global optimum solution was found by using the genetic algorithm in the proposed model.

Various methods have been used to regulate congestion issue. Saini and Saxena [10], developed a concept of congestion penalty factors and it was employed to control power over flows in lines to alleviate congestion. Three methods based on optimal power flow (OPF) were proposed and tested. Bompard *et al.* [11], presented a comparative analysis of different schemes implemented to manage congestion. The unified framework was developed for evaluating the various congestion management techniques by using a consistent metrics set. Singh *et al.* [12] discussed two methods to deal with congestion cost. The former method depends on nodal pricing scheme and is proposed for the pool model. The second method depends on cost allocation measure, formed for the bilateral model. Yousefi *et al.* [13] developed a method for congestion management in which the traditional approach of using FACTS devices was supplemented by demand responses. A mixed integer optimization technique has been developed for the proposed method. Vijayakumar [14], proposed two proficient methods for congestion management by generator rescheduling in the day-ahead electricity market. The fuzzy evolutionary programming method and nondominated sorting genetic algorithm method were used. The viability of the proposed methods was tested on IEEE 30-bus test system for severe line outages. Manikandan *et al.* [15], compared two methods for congestion management namely, zone/cluster method and relative electrical distance (RED) method.

In the former method, generation rescheduling was done by using the transmission congestion distribution factors. In the later method, the desired proportions of generations for the required overload relieving were obtained. Vries [16] presented two congestion management schemes i.e., congestion pricing schemes and remedial schemes. The former provides proficient incentives to market participants and not to the network supervisors while the later provides incentives to the network managers and not to the participants.

The analysis of marginal prices for the optimal location of FACTS device can be done by using optimal power flow technique. LMP's or nodal prices are obtained from the result of the OPF. Either ACOPF or DCOPF, any model can be used for this purpose. Shanthini [17], discussed the analysis of location marginal pricing based DCOPF. LMP based on DCOPF for distributed and concentrated model was elucidated with fixed bids and linear bids. Decomposition of LMP was also carried out to ensure economic operation. Siddiqui [18] proposed a novel technique i.e., LMP technique for allocating and sizing the TCSC. This technique depends on the marginal prices which are obtained from the optimal power flow methods. The efficacy of the technique has been presented as it minimises the computational costs along with maximising the social welfare. Fangxing [19], presented new analytical equations to calculate the AC- based distribution factors and loss factors that only depend on the present operating point and system topology. Hence, proposed model was reference-independent. It also combines the fictitious nodal demand (FND) model into original LMP Model to obtain new loss distribution factors so that losses are distributed at each line to attain a fairer and more realistic model. Rui and Fangxing [20], presented a comparison of LMP values from lossless DCOPF, the FND-based Iterative DCOPF, and the ACOPF algorithms. The results showed that FND-based DCOPF gave better results than lossless DCOPF and thus represented a better approximation of ACOPF.

The series FACTS device are essential in improving the power transfer capability of the line and thus helpful in maintaining congestion. There are several methods which depend on location marginal prices and helps in obtaining the optimal place for FACTS device installation. Acharya *et al.* [21], proposed two methods, namely LMP difference and congestion rent contribution for installing series FACTS devices to reduce congestion in deregulated power market. These proposed methods were tested on three different IEEE test systems. Results showed that, unlike sensitivity methods where non-linearity is not captured, proposed methods correctly capture the best locations for series FACTS devices to manage congestion. Oliveira *et al.* [22], introduced the allocation of FACTS devices in electrical power system and their efficacy for a hydropower system. It has been proposed that the series compensation is the best alternative to control active flows. It was shown that the transmission loss is the main factor which needs to be considered for FACTS placement. The main FACTS devices that have been used for the congestion management purpose are TCSC, UPFC, and TCPAR. Ghawghawea and Thakre [23], discussed that congestion management can be realized by improving available transfer capability (ATC) of the network. For ATC improvement, FACTS devices such as TCSC and UPFC can be utilized. A new approach for determination of changes in TCSC reactance has been proposed to achieve desired transfer capability. The results showed that ATC is improved to a particular value by the placement of TCSC in the specified transmission line.

There are different models of the FACTS devices that can be utilized for the installation purpose. There are several advantages of TCSC power injection model over the other methods such as reactance model. Xiao *et al.* [24], presented a new approach for power flow control, based on the power injection model of FACTS devices which allows the integration of various FACTS devices in the existing power system. With the power injections of FACTS devices taken as control variables, jacobian matrix, and control model need not be restructured. Lehmkoster [25], presented an approach that combines suitable linear models for FACTS devices with a dominant optimization model including security constraints. The integration of FACTS devices into existing power systems has also been described. Besharat and Taher *et al.* [26], developed two sensitivity-based methods for determining the optimal location of thyristor controlled series compensators (TCSCs) for congestion management in deregulated power systems. The effect of TCSC on line outage, in order to reduce congestion, has also been presented. Esmaili *et al.* [27], proposed a multi-objective framework for locating TCSCs for congestion management in order to establish enough levels of voltage and transient stability margins after congestion management. Pareto solutions using the modified augmented e-constraint method were generated, and the most preferred Pareto solution was selected by a fuzzy decision maker. It was shown that multi-objective solution not only proposes a different branch to locate TCSC but also gave a more proficient solution than the conventional single objective solution.

Many researchers have used fuzzy based approach to locate FACTS devices, in order to overcome congestion problem. Ushasurendra and Parathasarthy [28], proposed a fuzzy method for optimal placement of thyristor controlled series compensator (TCSC) to control the real power flows for managing congestion. The fuzzy technique results were compared with the results given by conventional sensitivity method. There are some conventional techniques like linear programming, gradient method, newton method, quadratic programming, and interior point method, for getting the optimal power flow solutions. Linear programming method is quite an efficient one for DC optimal power flow model. Ziaee [29], investigated an approach to allocate TCSC based on mixed integer linear programming and Taylor series expansion. The necessity to approximate nonlinear constraints by first order taylor series due to the nonlinear nature of the allocation problem has been proposed. Some researchers have also implemented other FACTS devices like UPFC and TCPAR for alleviating congestion. Suganya *et al.* [30], implemented a cost-free method for managing congestion in deregulated power system. The unified power flow controller (UPFC) was used to relieve congestion and the proposed method was tested on IEEE 30-bus test system. Thota and Hameed [31], developed a fuzzy method for optimal location of unified power flow controller (UPFC) to control real power flows for congestion management. The advantage of the developed method was to form the priority list so that only a few lines in the priority list need to be inspected in detail to find the best location to manage congestion.

In recent years, AI techniques have been developed and utilized by the researchers because of their fast convergence rate and capability to depict global solution for the problem. Murali *et al.* [32], presented genetic algorithm (GA) based security constrained economic dispatch (SCED) approach for LMP calculation. In this approach, LMP's at all buses for a constrained transmission system while minimizing total system fuel cost, with and without considering transmission system losses, were evaluated. It was shown that GA approach has a reliable convergence with optimal fuel cost values. Kumar *et al.* [33], presented a genetic algorithm to manage congestion in deregulated electricity market by incorporating FACTS devices using OPF technique. A genetic algorithm was used to find optimal location of unified power flow controller (UPFC). The results were obtained for IEEE 30-bus test systems and compared with the static VAR compensator (SVC). Nabavi *et al.* [34], proposed a genetic algorithm and implemented it to minimize the total generation cost in power systems. A significant reduction in total cost of the system was shown by simulation results for IEEE 30-bus test system. A fine accuracy for the proposed approach to manage congestion has been illustrated by using the power world simulator software.

In order to overcome drawbacks of conventional techniques, marginal loss pricing model was introduced to account for the system losses. Litvinov *et al.* [35], presented a marginal loss pricing model developed mutually by the ISO New England and ALSTOM energy automation and information (EAI). In this method, losses have been balanced accurately at selected locations in the transmission system. It was shown that the model was invariant to the selection of the reference bus for constraint sensitivities and losses. Motamedi *et al.* [36], presented a novel transmission planning framework for partially deregulated power markets. The interrelated problems namely, GENCOs bidding strategies, generation expansion, and market clearing were solved by linking agent based and search based algorithms. The proposed framework was applied to a 5-bus test system, and the simulation results have been converged to optimal transmission plan. Verma *et al.* [37], proposed a new meta-heuristic algorithm, known as symbiotic organisms search (SOS) algorithm to manage congestion in pool-based electricity market by generation rescheduling of active power. It has been presented that proposed SOS algorithm is a population-based algorithm which does not need any control parameters, unlike other algorithms. The effectiveness of the proposed algorithm for obtaining the higher quality solution has also been ascertained.

1.3 Objective of the Work

The objective of the dissertation is to employ the congestion management techniques. There are two means, one is generation re-dispatch and another one is by placing FACTS device in the most optimal location for alleviating congestion. Two methods, namely LMP difference method and congestion rent contribution method are used for finding the best location for TCSC placement. The above methods are examined for IEEE 14 and IEEE 30-bus test systems. Genetic algorithm

(GA) based DCOPF is used to evaluate LMP's at all buses while minimizing the generation costs. The comparison is made between linear programming (LP) DCOPF using the fictitious nodal demand (FND) model (to avoid mismatch at the reference bus) and GA based DCOPF while considering the losses. The generation dispatch using GA technique results in significant savings in the generation costs compared to LP approach.

1.4 Dissertation Organization

The dissertation titled as - "Allocating TCSC for transmission congestion management in deregulated environment" has been organised in five chapters. **Chapter 1** deals with an overview, literature survey, and objective of the dissertation. **Chapter 2** describes the various congestion management schemes, mathematical formulation of the problem, and optimal power flow with TCSC. **Chapter 3** presents the optimal power flow (OPF) techniques. A conventional linear programming technique and AI genetic algorithm have been discussed. **Chapter 4** provides the results and discussions for two test systems. The Test I consists of IEEE 14-bus system and Test II consists IEEE 30-bus system. Both the OPF techniques have been compared and analysed for the generation cost and LMP values. The GA technique proved its superiority over the former technique and hence used to point optimum location for FACTS device placement. The conclusion and future scope of work has been mentioned in **Chapter 5** followed by the publications, bibliography, and appendix.

Chapter 2

Congestion Management Schemes

2.1 General Concept

In restructured power system, distinct entities compete among each other for drawing private investment in order to encourage technical development resulting in improved efficiency and consumer contentment [1], [2]. With escalating number of bilateral transactions in the electricity market, it is difficult to avoid congestion problem. Congestion is the fundamental concern of transmission management system. In congestion, more power flows across transmission line than its physical limits. When transmission line operates near to its thermal limit, the system operators gets restricted to dispatch more power from cheaper generator [3]. Consequently, there is in an overall increase in the power dispatching cost. The probable limits that might hit in the case of congestion are thermal limits of the line, bus voltage limits, transient stability etc. These limits confine the amount of transmitted power. In this circumstance, congestion management becomes an important concern. It is the process to manage or reduce the congestion. It is considered as an efficient method for scheduling and matching generation and demand.

2.1.1 Methods for congestion management

Independent system operator can use primarily two types of methods to relieve congestion:

1. Cost free methods
    - Outage of congested/overloaded lines.

- The operation of transformer taps/phase shifters.
- The operation of series FACTS devices.

Flexible AC transmission systems (FACTS) device is a power electronic-based device which has the ability to augment controllability and increase power transfer capability. At the present time, system operators face concerns like rising demand for bulk power delivery, advanced reliability, and low priced power deliverance. These issues may be relieved by FACTS technology, [4], [5]. FACTS can be connected in series or in shunt or even in combined form with the transmission line. Series capacitors and unified power flow controllers (UPFC) are mostly used to increase the power transfer capability in the lines which may result in reduced line losses and improved stability. Therefore incorporating FACTS device into the congestion management turn out to be more reliable and popular.

2. Non-cost-free methods

- Re-dispatch of generation.
- Curtailment of loads or load shedding.

In generation re-dispatch method, the system operator re-dispatches the generation in order to alleviate congestion [6]. It involves system operator to purchase power from high-cost areas. The low-cost areas generators are directed to adjust downwards. As the ISO is purchasing power at high cost and selling at a lower cost, so he earns a cost. The cost acquired by system operator signifies the congestion cost. The ISO directs generator to adjust generation up or down devoid the market use. Congestion can be alleviated to some extent by regulating load also. But the amount of load shedding should be small and the cost should be reduced in the congested area. There are various curtailment algorithms, a term willingness-to-pay to avoid curtailment was presented in [38]. It is considered as an efficient tool in setting the load curtailment.

Among the above two methods, cost-free methods have advantages as they do not touch economic matters, so GENCOs and DISCOs will not be engaged. Hence, FACTS devices are utilized to reduce the transmission congestion. The main concerns related to the use of FACTS devices are the proper location, appropriate setting, size, cost, and modeling. FACTS device like TCSC can be used to alleviate congestion in the transmission network. Two methods, namely LMP difference method and congestion rent contribution method, are employed to find the optimal location for TCSC installation [21]. The methods depend on upon the locational marginal pricing (LMP) difference and line flows. The best place to install TCSC is that which gives minimum contribution in total congestion rent or minimum generation cost.

2.1.2 Deregulated power market pricing structure

There are two pricing schemes of deregulated electricity market: The uniform pricing method known as market clearing prices and the non-uniform pricing method known as locational marginal prices, both are derived from generators offers to sell electricity. In the first method, the market clearing price is set based on the last accepted offer and is uniform. The second method i.e., LMP is the common process in power markets for nodal prices calculation and to regulate congestion. Buyers pay independent system operator (ISO) depending on their LMP for the transmitted energy and the ISO pay suppliers depending on their particular LMP's [7], [32]. LMP consists of three components and is expressed as:

LMP = energy component + loss component + congestion component

Calculation of LMP in a market environment involves solving an optimization problem. LMP is the by-product of the solution to this optimization problem. The LMP models can be mainly classified as AC optimal power flow model and DC optimal power flow model. The ACOPF model employs the AC formulation to signify line flows. Hence, it can accurately represent the power flows and the line losses. In contrast, the DCOPF model depends on DC power flow approximation, therefore, less accurate. ACOPF gives more precise and accurate LMP's but modeling its constraints is quite complicated. Therefore, not used for real-time applications. Hence, mostly power markets utilize DCOPF models for the purpose of market clearing [17], [20]. Following are the advantages of DCOPF:

1. Ease of implementation
2. Fast convergence speed
3. Accessibility to LMP components

2.1.3 Methods for optimal placement of FACTS device

Two following methods are employed for optimal placement of TCSC. Both the methods are the function of location marginal prices (LMP's) or nodal prices. Therefore, known as pricing methods.

1. LMP difference method

In this method, LMPs or nodal prices are utilized to choose the best location for TCSC placement in order to reduce congestion. As LMP consists of 3 components, namely energy component, loss component, and congestion component. The LMP difference between two buses indicates the congestion level in a line. The difference in LMP is more for the overloaded lines but these lines may not be necessarily the best place for installation of FACTS device. Hence, a neighborhood technique is needed so that a priority based listing can be formed depending on the LMP difference value. This listing is able to confine both overloaded and neighborhood lines so that power is able to be averted after FACTS placement.

The LMP difference between buses j and k is stated as:

$$\Delta LMP_{jk} = (LMP_j^{cong} - LMP_k^{cong}) + (LMP_j^{loss} - LMP_k^{loss}) \tag{2.1}$$

2. Congestion rent contribution method

This method is more reliable and accurate in giving the best location for TCSC placement. As it does not depend solely on LMP difference values but also on power flow through lines. The former method is simple in implementation but that is not suitable in cases where low rating line is overloaded. Now due to overloading, the LMP difference value will be high across that line but its effect on market participant because of congestion rent might be insignificant. Therefore, in this method priority listing is done on the basis of congestion rent which is known as a product of LMP difference and power flow of the line. The involvement of each line in the congestion rent can be obtained as:

$$CC_{jk} = \Delta LMP_{jk} \times P_{jk} \tag{2.2}$$

where LMP_{jk} is the LMP difference between buses j and k and P_{jk} is the power flow across line connected between buses j and k.

The contribution of each line in the overall congestion rent is given by an index, which is obtained as:

$$CCC_{jk} = \frac{CC_{jk}}{TCC} \tag{2.3}$$

where TCC is known as total congestion rent and is evaluated as:

$$TCC = \sum_{jk=1}^{n_b} \Delta LMP_{jk} \times P_{jk} \tag{2.4}$$

2.2 Problem Formulation

2.2.1 DC load flow

The analysis of load flow is essential for the economic operation of power system. The DC load flow is quite helpful in this regard [39]. It shows the estimation of line flows on AC system. In this, only active power is considered and reactive power is neglected. It is a non-iterative and convergent process. But the AC load flow methods are more accurate. Typically DC load flow is used when quick and repetitive evaluation of load flow is needed. In DC load flow, following assumptions are made to simplify nonlinear model into a linear one:

1. The resistance of lines is neglected.
2. The voltage magnitudes are set equal to 1 per unit.
3. The lines losses are ignored.
4. The angle differences of voltage are presumed to be small. So, $sin(\theta) = \theta$, $cos(\theta) = 1$.
5. The transformer tap settings are neglected.
6. The reactive power balance equation is overlooked.

Therefore, dc load flow changes the model into linear one. The power injection at every bus j is given by:

$$P_j = \sum_{k=1}^{n_b} B_{jk}\,(\theta_j - \theta_k) \tag{2.5}$$

where P_j is the active power injection at bus j, B_{jk} is inverse of reactance of line connected between buses j and k (imaginary part of Y_{jk}), and θ is the angle of bus voltage.

In the matrix form, it can be represented as:

$$\theta = [B^{-1}]\,P \tag{2.6}$$

where θ is vector of voltage angles, B is susceptance matrix (R = 0), and P is vector of bus power injections.

The power flow across transmission line between buses j and k can be formulated as:

$$P_L = \frac{(\theta_j - \theta_k)}{X_L} \tag{2.7}$$

where X_L is the reactance of line.

2.2.2 Lossless DCOPF

The lossless DCOPF model is modeled for the total generation cost minimization subject to the power balance and line flow constraints [17]. The formulation of lossless DCOPF is given below:

$$Min \quad \sum_{j=1}^{n_g} C_j \times P_{G_j} \tag{2.8}$$

$$s.t. \quad \sum_{j=1}^{n_b} P_{G_j} = \sum_{j=1}^{n_b} P_{D_j} \tag{2.9}$$

$$\sum_{j=1}^{n_b} GSF_{(m,j)} \times (P_{G_j} - P_{D_j}) \leq limit_m, \;\; for \;\; m = 1,2,......,K \tag{2.10}$$

$$P_{G_j}^{min} \leq P_{G_j} \leq P_{G_j}^{max}, \;\; for \;\; j = 1,2,......,n_g \tag{2.11}$$

where n_g is the number of generators, n_b is number of buses, K is number of lines, C_j is cost of generation at bus j, P_{G_j} is generation at bus j, P_{D_j} is demand at bus j, $P_{G_j}^{max}$ and $P_{G_j}^{min}$ are maximum and minimum output generation at bus j, $limit_m$ is thermal limit of line m, and $GSF_{m,j}$ is generation shift factor of line m at bus j. The $GSF_{m,j}$ is described as change in power flow of line m when there is change in power injection at bus j. It can be computed as:

$$GSF_{m,j} = \frac{(B_{a,j}^{-1} - B_{b,j}^{-1})}{X_m} \tag{2.12}$$

2.2.3 Loss factor and delivery factor

For including the influence of losses on LMP, loss and delivery factor have to be considered. To serve the load at a bus, effective MW delivered to purchaser is known as the delivery factor at that bus. Mathematically, it is defined as:

$$DF_j = 1 - LF_j = 1 - \frac{\partial P_{Loss}}{\partial P_j} \tag{2.13}$$

where DF_j is the delivery factor at bus j, LF_j is the loss factor at bus j, P_{Loss} is the total loss, and P_j is injection at bus j. According to the loss factor definition [40], P_{Loss} is given as:

$$P_{Loss} = \sum_{m=1}^{K} F_m^2 \times R_m \tag{2.14}$$

$$\frac{\partial P_{Loss}}{\partial P_j} = \frac{\partial}{\partial P_j}\left(\sum_{m=1}^{K} F_m^2 \times R_m\right) \tag{2.15}$$

where F_m is the power flow of line m and R_m is the resistance of line m.

The line flows can be considered as the summation of the inputs from all sources of power. Mathematically, it is defined as:

$$F_m = \sum_{i=1}^{n_b} GSF_{(m,i)} \times (P_{G_i} - P_{D_i}) = \sum_{i=1}^{n_b} GSF_{(m,i)} \times P_i \tag{2.16}$$

It can be expanded further as:

$$\begin{aligned}\frac{\partial P_{Loss}}{\partial P_j} &= \sum_{m=1}^{K} \frac{\partial}{\partial P_j}(F_m^2 \times R_m) \\ &= \sum_{m=1}^{K} R_m \times 2F_m \times \frac{\partial F_m}{\partial P_j} \\ &= \sum_{m=1}^{K} 2 \times R_m \times GSF_{(m,j)} \times (\sum_{i=1}^{n_b} GSF_{(m,i)} \times P_i) \qquad (2.17)\end{aligned}$$

2.2.4 DCOPF considering marginal loss

In DCOPF iterative method, the results of dispatch from the i^{th} iteration is utilized to revise the approximated DF_j and P_{Loss}. DCOPF is evaluated in every iteration. The loss factors may affect the generation dispatch, therefore, the energy balance constraint get modified [35] and can be formulated as:

$$\sum_{j=1}^{n_b} DF_j^{est} \times P_{G_j} - \sum_{j=1}^{n_b} DF_j^{est} \times P_{D_j} + P_{Loss}^{est} = 0 \qquad (2.18)$$

where DF_j^{est} is the delivery factor from prior iteration at bus j and P_{Loss}^{est} is P_{Loss} from prior iteration.

2.2.5 FND-based iterative DCOPF algorithm

The cost of marginal loss is handled by the consideration of delivery factors. Although, constraints of line flow in equation (2.10) presumed a lossless system. While the constraint of power balance in equation (2.18) implements that overall generation must be greater than overall demand load by the transmission system loss. This might results in a mismatch at the system slack bus as the value of difference or mismatch has to be taken up by slack bus. To address this problem, it is enviable to signify system losses in the transmission lines.

The model of FND is employed in the paper to signify the line losses. To reduce the power balance difference at the slack bus, FND is used to allocate losses of the system amongst each line [19], [20]. With this approach, the loss gets divided into two equal halves in each transmission line and every half is shown as added demand at a node. At every bus, FND is represented as the sum of corresponding transmission line losses.

FND at any bus j is denoted as E_j and is represented as:

$$E_j = \sum_{m=1}^{K_j} \frac{1}{2} \times F_m^2 \times R_m \tag{2.19}$$

where K_j is the number of lines attached to bus j.

From FND computation, line flows can be evaluated. Now, line flow F_m is represented as:

$$F_m = \sum_{j=1}^{n_b} GSF_{(m,j)} \times (P_{G_j} - P_{D_j} - E_j^{est}) \tag{2.20}$$

Hence, the new DCOPF model can be formulated as:

$$Min \quad \sum_{j=1}^{n_g} C_j \times P_{G_j} \tag{2.21}$$

$$s.t. \quad \sum_{j=1}^{n_b} DF_j^{est} \times P_{G_j} - \sum_{j=1}^{n_b} DF_j^{est} \times P_{D_j} + P_{Loss}^{est} = 0 \tag{2.22}$$

$$\sum_{j=1}^{n_b} GSF_{(m,j)} \times (P_{G_j} - P_{D_j} - E_j^{est}) \leq limit_m \tag{2.23}$$

$$P_{G_j}^{min} \leq P_{G_j} \leq P_{G_j}^{max} \tag{2.24}$$

where $m \in$ all lines and $j \in$ all generators. The LMP can be evaluated at any bus j by using the Lagrangian function. This function is represented as:

$$Ł = (\sum_{j=1}^{n_g} C_j \times P_{G_j}) - \lambda(\sum_{j=1}^{n_b} DF_j \times P_{G_j} - \sum_{j=1}^{n_b} DF_j \times P_{D_j} + P_{Loss})$$

$$- \sum_{m=1}^{K} \mu_m (\sum_{j=1}^{n_b} GSF_{(m,j)} \times (P_{G_j} - P_{D_j}) - limit_m) \tag{2.25}$$

LMP at any bus j is given as:

$$LMP_j = \frac{\partial Ł}{\partial P_{D_j}} = \lambda \times DF_j + (\sum_{m=1}^{K} \mu_m \times (GSF_{(m,j)}))$$

$$= \lambda + (\sum_{m=1}^{K} \mu_m \times GSF_{(m,j)}) + \lambda(DF_j - 1) \tag{2.26}$$

where λ is the price at the slack bus, LMP_j is LMP at bus j and μ_m is the constraint cost of line m. The μ_m is described as ratio of incremental change in the overall cost to the incremental change in flow of lines.

LMP in equation (2.26) can be partitioned into the following 3 components: energy component, loss component, and congestion component [6], [7]. Therefore LMP may be represented as:

$$LMP_j = LMP^{energy} + LMP_j^{cong} + LMP_j^{loss} \tag{2.27}$$

$$LMP^{energy} = \lambda \tag{2.28}$$

$$LMP_j^{cong} = \sum_{m=1}^{K} GSF_{(m,j)} \times \mu_m \tag{2.29}$$

$$LMP_j^{loss} = \lambda \times (DF_j - 1) \tag{2.30}$$

2.3 Optimal Power Flow with TCSC

2.3.1 TCSC modeling

In the presented work, power injection model of TCSC has been implemented. In this model, FACTS acts as a tool that infuse active and reactive power into the node [4]. It depicts that the operation of the controller is replicated by the injection flows. The benefit of this model is that there is no need to structure admittance matrix again and permits the proficient incorporation of FACTS into the transmission system.

The TCSC incorporated in the transmission line is shown in Fig. 2.1. Here line connected between two buses is characterized by pi equivalent lumped parameters. In the steady state, TCSC

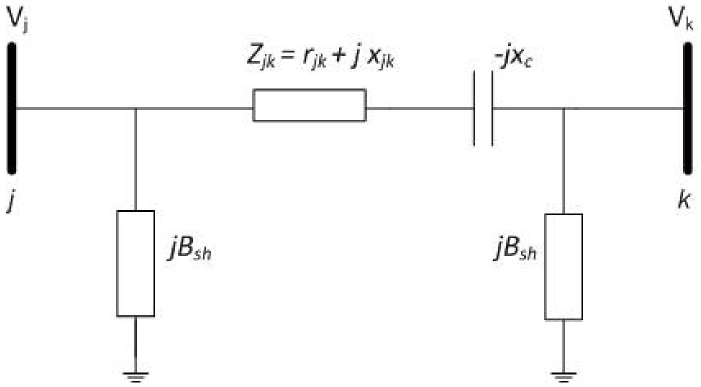

Figure 2.1: TCSC located in Transmission line.

may be regarded as reactance -jx_c. In load flow equations, x_c (controllable reactance) is treated as a control variable. The transmission line reactance is altered in the mathematical model of TCSC which permits it to function as capacitor or inductor compensator [27]. Fig. 2.2 presents the equivalent power injection model.

On the basis of a DC power flow approach, the real power flow along the transmission line between buses j and k with TCSC, is formulated as:

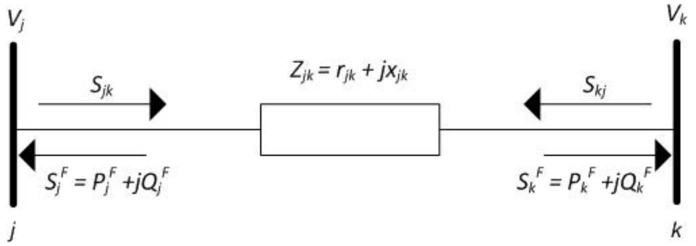

Figure 2.2: Power injection by TCSC.

$$P_{jk} = b_{jk}(\theta_j - \theta_k) \tag{2.31}$$

The active power injections at buses j and k after installation of TCSC are:

$$P_{F,j} = \frac{X_{TCSC}}{X_{jk}.(X_{jk} - X_{TCSC})}(\theta_j - \theta_k) \tag{2.32}$$

$$P_{F,k} = -\frac{X_{TCSC}}{X_{jk}.(X_{jk} - X_{TCSC})}(\theta_j - \theta_k) \tag{2.33}$$

2.3.2 Formulation of OPF with TCSC

In deregulated power market, OPF solution is used for the calculation of nodal prices or LMP's. In the case of elastic demand, it depends on submitted generator and load bids and the data information of the system. Mathematically, it is formulated as:

$$Min \quad \sum_{j=1}^{n_g}(C_j \times P_{G_j}) - \sum_{j=1}^{n_d}(B_j \times P_{D_j}) \tag{2.34}$$

where n_g is the number of generators, n_d is the number of loads, $(C_j \times P_{G_j})$ is bid curve of j^{th} generator, and $(B_j \times P_{D_j})$ is benefit curve for j^{th} demand. When TCSC allocation is between buses j and k, the line flow constraints remains the same as in classical DCOPF problem, i.e., equation (2.23), but energy balance constraint gets modified from equation (2.22) and the transmission line power transfer capacity will rise as there will be an enhancement in stability. The power balance equations are given by:

for node j,

$$P_j - P_{G_j} + P_{D_j} + P_{F,j} = 0 \tag{2.35}$$

for node k.

$$P_k - P_{G_k} + P_{D_k} + P_{F,k} = 0 \tag{2.36}$$

where P_j is the net active power injection at node j, P_k is the net active power injection at node k, $P_{F,j}$ is the power injection at node j due to TCSC installation, $P_{F,k}$ is the power injection at node k due to TCSC installation, P_{G_j} is active power generation at node j, and P_{D_j} is power demand at node j.

In the presented work, the deregulated environment condition is assumed i.e., demand is inelastic. Price elasticity of load/demand measures the response of load/demand to changes in price. When the price elasticity of load is zero then load is perfectly inelastic. It means load does not change when price changes. In today's deregulated power markets, demand side does not participate actively in the price setting course which results in failure of balancing variations in generation and demand. When the demand is inelastic, the objective function given by equation (2.34) becomes the total cost of supplying generated power. Now the objective function is given by the minimization of generation cost:

$$Min \sum_{j=1}^{n_g} (C_j \times P_{G_j}) \tag{2.37}$$

2.3.3 Procedure

The procedure of calculation for employed methods to find the optimal location of TCSC is described by following steps:

1. Perform the base case optimal power flow to evaluate power flow of each line and LMP at each bus.
2. Compute the difference in the value of LMP's and sort them to create a list based on the priority according to their magnitude value.
3. Evaluate contribution of each line in total congestion rent by using equations (2.1) to (2.4) and organize them in the list based on the priority according to their magnitude value.
4. Now, perform generation dispatch for every transmission line with TCSC and then compute overall congestion rent and total cost of production.
5. The optimal place for TCSC installation is the one which provide minimum cost of congestion or minimum cost of production.

Chapter 3

DCOPF Implementation Techniques

3.1 Linear Programming

3.1.1 Introduction

The progress of linear programming has been done over the 50 years. The tremendously competent algorithms have been developed so far, in order to solve large linear programs very fast. Moreover, there are various software packages that compute LP solutions quite easily. It entails maximizing or minimizing a linear objective function that is subjected to linear equality, and inequality constraints.

LP is a particular case of mathematical programming. In a mathematical model, linear optimization is a technique to attain the best result, like minimum total cost. In this model, requirements are characterized by linear relationships. Most of the power markets use linear programming based security constrained optimal power flow. In this, security constraints are present which are related to the line overloads. The DCOPF approach is typically used for the computation of LMPs by linear programming model, because LP is quick and robust in giving the results. The DCOPF approach fits naturally in the LP model [19]. For LP's application, quadratic fuel cost curve may be shown as piecewise linear curves.

In OPF linearization, it is assumed that single price offer is made by every generator. Therefore, each individual generating unit is shown as a constant multiplied by generation level in the objective function.

$[x,\ fval,\ exitflag,\ output,\ lambda] = linprog\ (H,\ A,\ b,\ Aeq,\ beq,\ lb,\ ub,\ x^0,\ options)$ characterizes a set of lower and upper bounds on the variable x, so that the solution is always in the limit $lb \leq x \leq ub$. *Aeq* and *beq* are set as a null matrice and vector, respectively if no equalities exist.

Linear programming problems are solved by '*linprog*'. It minimizes the problem which is described as:

$$Min\ \ f^T x\ \ subject\ \ to \begin{cases} A\ .\ x \leq b, \\ Aeq\ .\ x\ = beq, \\ lb \leq x \leq ub. \end{cases} \tag{3.1}$$

where f is the linear objective function i.e., cost function, A is matrix of linear inequality constraints, b is vector of linear inequality constraints, Aeq is matrix of linear equality constraints, beq is vector of linear equality constraints, lb is vector of lower limits of generation, ub is vector of upper limits of generation, x^0 is preliminary point for solution variable x, and *options* is the structure formed with the *optimset*. The *option* creates or edits optimization options structure.

Here, inequality constraint is power flow in lines, stated as:

$$\sum_{j=1}^{n_b} GSF_{(m,j)} \times (P_{G_j} - P_{D_j} - E_j^{est}) \leq limit_m, \tag{3.2}$$

And equality constraint is the power balance equation, stated as:

$$s.t.\quad \sum_{j=1}^{n_b} DF_j^{est} \times P_{G_j} - \sum_{j=1}^{n_b} DF_j^{est} \times P_{D_i} + P_{Loss}^{est} = 0 \tag{3.3}$$

x, $fval$, $exitflag$, $output$, and $lambda$ are the output arguments. These are the arguments returned by *linprog*.

1. The varaible '*x*' gives the output generation of every generating unit.
2. The term '*fval*' gives the value of objective function at the solution *x*.
3. The term '*exitflag*' is the integer which recognizes the reason of algorithm termination. The following lists the exitflag values and the subsequent causes for termination:
    - 1 : This value shows that the function gets converged to a solution *x*.
    - 0 : It tells that the number of iterations gets exceeded.
    - -2 : It illustrates that there is no feasible point present.
    - -3 : It shows that the problem is unbounded.
    - -4 : It shows that NaN value came across during algorithm implementation.
    - -5 : It tells that the primal and dual problems, both are infeasible.
    - -7 : It depicts that the search direction became very small. Any additional improvement could not be made.
4. The term '*output*' denotes the structure which contains information of the optimization. The structure fields are:
    - iterations : It denotes the number of iterations.
    - algorithm : It tells about the algorithm that is used for optimization.
    - cgiterations : If this value comes to be 0, then it means that only large-scale algorithm is included for the backward compatibility.
    - constrviolation : It tells the maximum of the constraint functions.
    - message : This is the exit message.

5. The term '*lambda*' denotes the structure which contains the Lagrange multipliers at the solution *x*. The structure fields are:
    - lower : It represents the lower bounds (*lb*) of generating limit.

- upper : It represents the upper bounds (*ub*) of generating limit.
- ineqlin : It shows the linear inequalities.
- eqlin : It shows the linear equalities.

The optimization options used by *linprog* are medium-scale and large-scale algorithms. In the medium-scale algorithms '*simplex*'option is used [41]. In this, if the value is 'on', *linprog* uses the simplex algorithm. This algorithm uses a built-in starting point, ignoring the starting point (x^0) if applied. If 'off', *linprog* uses an active-set algorithm. While, in large-Scale algorithms, the method is based on Linear Interior Point Solver, which is a variant of Mehrotra's predictor-corrector algorithm, a primal-dual interior-point method. A number of preprocessing steps occur before the algorithm begins to iterate.

3.1.2 Algorithm

The teps to calculate LMP using LP:

1. Set loss factor $LF_j^{est} = 0$, delivery factor $DF_j^{est} = 1$, FND $E_j^{est} = 0$, for all the buses and loss $P_{Loss}^{est} = 0$.
2. Set the values in matrix A and vector b considering the inequality constraint i.e., power flow in lines.
3. Set the values in matrix Aeq and vector beq considering the equality constraint i.e., power balance equation.
4. Set the lower and upper limits of generation units.
5. Now by using equations (2.21) to (2.24) execute the generation dispatch.
6. Update LF_j^{est}, DF_j^{est}, E_j^{est}, and P_{Loss}^{est} using equation (2.13), (2.14), (2,17), and (2.19).
7. Update values of A, b, Aeq, and beq for considering the loss case.
8. Execute another dispatch using equations (2.21) to (2.24).

9. Verify the dispatch output of every generator with the prior dispatch. When the difference is more than the specified tolerance, go to step 5, else go to step 10.

10. Compute all the 3 components of LMP at each bus by using equations (2.27) to (2.30).

3.2 Genetic Algorithm

3.2.1 Introduction

There are various techniques for solving an optimization problem, for ex. - Ant colony method, particle swarm optimization (PSO), differential evolutionary algorithm (DEA), and genetic algorithm (GA). These all are search techniques depending on the population. Among all these methods, genetic algorithm is the easiest and robust one and therefore it is preferred over other techniques [32], [33]. This technique is different from conventional techniques in following ways:

1. In GA, the operation is done on a string of parameters of specified problem instead of actual parameters.

2. It utilizes a number of points in search instead of a single point.

3. It does not need any aforementioned knowledge, limitation of space, and properties of the objective function. It only needs the computation of fitness function to allocate an eminent value in each resulted solution.

4. It does not use deterministic rules but the probabilistic rules.

It is a technique which depends on the genetics and natural selection [34]. It functions on chromosomes which consist of genes. The phenotype is the control parameter whose value gets stored in a gene and is known as an allele. The optimization method success is based on the suitable fitness function [42]. In a particular population, the fitness function value is used to drive the procedure of evolution. It allows the GA to show good results when a complex or discontinuous functions are optimized. The genetic operations are carried out in the population for the evolution purpose in GA. Following are the fundamental genetic operations:

1. Selection

2. Crossover

3. Mutation.

Selection- In this operation, individuals are selected depending on the fitness value from the current or parent population and copied to the new population. So, the individuals which have higher values of fitness function are more probable to get select to the next generation.

Crossover- The crossover operation is exceptionally significant as it is accountable for the recombination of binary strings. In this operation, a crossover site is selected first. Then two parents are selected to create new individuals, so binary string from starting to the crossover point is copied from one parent, the rest is copied from the other parent. It is a random process that takes place with a predefined probability. It is generally used with high probability rate, i.e., 0.7 to 0.9. There are many crossover schemes, like single point crossover, multi-point crossover, and uniform crossover.

Mutation- The mutation operation is utilized to keep genetic diversity from one generation to the next generation of the population. It alters bits from 1 to 0 and vice-versa with a low probability, i.e., 0.01 to 0.05 to increase diversity in the newly generated population. It is also a random process and takes place with predefined probability.

The GA technique can be utilized for optimal power flow method to place FACTS device in the most optimal location. The GA can be integrated with conventional OPF method to choose the best control variables in order to minimize the total generation cost while maintaining all the security limits of line flows [43], [44].

3.2.2 Algorithm

The steps to calculate LMP using GA:

1. Read bus data, line data, cost data, number of buses, number of lines, chromosome length, size of population, crossover and mutation probability.

2. Randomly generate and decode the power generations of every generator excluding the reference bus generator.

3. Compute the generation shift factors by using equation (2.12).

4. Evaluate the line power flows by using equation (2.16).

5. Calculate the loss of the system i.e., P_{Loss} by using equation (2.14).

6. Compute delivery factors for every bus by using equation (2.13).

7. Compute reference bus generation for loss case by using equation (2.18).

8. Verify the limits of line power flows by using equation (2.20). Add the penalty to the objective function according to the penalty function approach, if limits get breached. Penalty function for power flows of lines is given as:

   $$pc\_lf = lambda\_lf(m) * d\_lf * (Pflow(m) - limit)^2$$

   where *lambda_lf(m)* and *d_lf* are constants.

9. Verify the limits of reference bus generation by using equation (2.24). Add the penalty to the objective function according to the penalty function approach, if limits get breached. Penalty function for reference bus power is given as:

   $$pc\_ref = lambda\_ref * d\_ref * (Pgen(1) - limit)^2$$

   where *lambda_ref* and *d_ref* are constants.

10. Compute the fuel costs of every generating unit. Then evaluate total generation cost by using equation (2.21) and fitness function by:

    $$FF = \frac{100}{(1 + total\ fuel\ cost + penalty)}$$

11. Arrange the chromosomes fitness value in the descending order.

12. Perform selection, crossover, and mutation of parents to create new individuals or offsprings.
13. Replace less fit individuals with new individuals Increase the generation count. i.e., generation = generation +1.
14. Check the convergence criteria i.e., Is fitness of all the individuals are same ? If yes, the problem is converged, else go to step 10.
15. After convergence criteria is met, calculate the slack bus energy price and compute LMP at every bus by using equations (2.27) to (2.30).

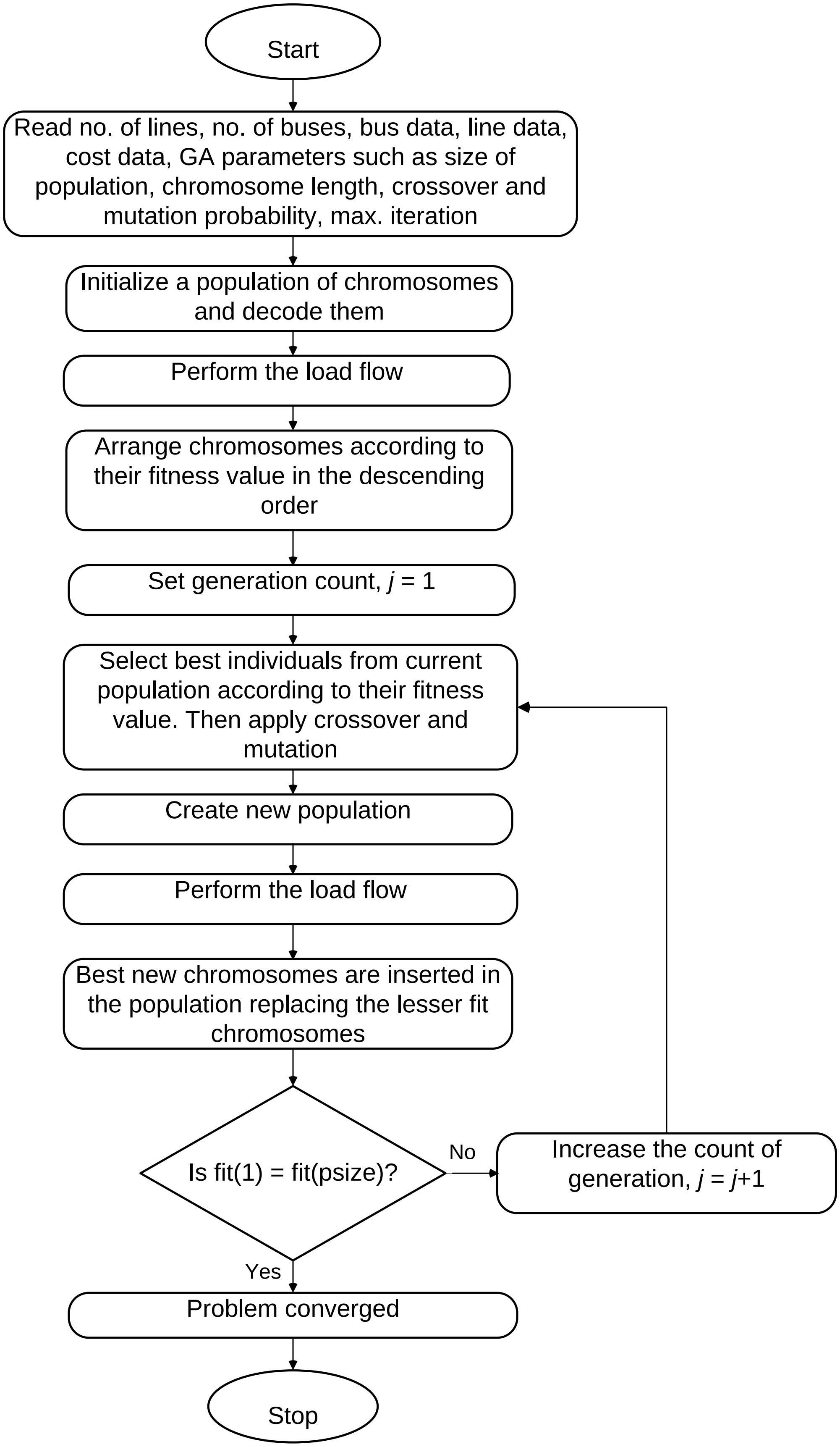

Figure 3.1: Flowchart of GA for congestion management

Chapter 4

Results and Discussion

The employed methods for TCSC optimal placement have been implemented on two test systems namely, IEEE 14-bus and IEEE 30-bus test systems. The bus data and line data has been taken from reference [41]. The cost data of both the test systems has been mentioned in Appendix A.

Two techniques have been used for the analysis of LMP at every bus namely, LP technique and GA technique. In the later technique, parameters used are- size of the population is 40, 12 bits are used for each generating unit except reference bus, crossover probability is 0.80, mutation probability is 0.01, and maximum number of iterations is 100.

The GA technique has been compared with DCOPF based LP technique for the optimal solution and the LMP values while considering the losses. In FND based LP technique, line losses have been partitioned into two halves and added to the nodes of buses to which the line is connected. It has been implemented to evade mismatch at the slack bus.

4.1 Test System 1: IEEE 14-Bus System

IEEE 14 bus system consists of 5 generators, 14 buses and 20 lines. In this case as there four generating units excluding the slack bus. Therefore, the value of GA parameter i.e., chromosome length has been taken as 48.

Table 4.1 shows the generated real power of all the generating units and the total generation cost while considering the losses. It has been depicted, that in comparison to LP technique, re-dispatch of generation using the GA technique results in significant savings in the generation costs. The value of LMP at every bus is illustrated in Table 4.2. It has been shown that the loads which are far from generating units have high LMP value due to the accumulation of loss and congestion cost.

The result for this test system is presented in Table 4.3 to 4.5. Table 4.3 shows the OPF results after TCSC placement for best ten locations to obtain minimum overall production cost and minimum overall congestion rent, for fixed bids. It is shown that Line 2: 2-3, is the most optimal location in order to get minimum congestion rent i.e., 638.34 $/h. In a similar way, to obtain minimum production cost, the first optimal location is line 1. It has a total generation cost of 8264.5 $/h. Now, these optimal locations should be confined by the employed methods. This will prove the efficacy of methods.

Table 4.1: Generator real power considering losses

Gen. bus no.	**Generated power in MW**	
	LP technique	**GA technique**
1	151.070	167.899
2	19.968	28.281
3	66.323	10.791
6	30.229	55.066
8	10.000	10.374
Generation cost ($/hr)	8818	8418

Depending on the difference of LMP values, best locations are shown in Table 4.4 for TCSC installation. Now, as the table 4.3 show that the best place to install TCSC is Line 2: 2-3, for minimum congestion rent. In a similar way, to obtain minimum production cost, Line 1: 1-2, is the best place. These both the lines are present in LMP difference method priority list. So this proves that method of LMP difference is effective.

The best locations for TCSC installation, depending on the contribution of congestion rent are presented in Table 4.5. Now the Table 4.3 depicts that the best place to install TCSC for minimization of congestion rent is Line 2: 2-3, and it has third place in the priority list in Table 4.5. But for minimizing the production cost, the best location is Line 1: 1-2, and it has first place in the priority list in Table 4.5. So, both the lines are present in the priority list of congestion rent contribution method.

After locating TCSC on Line 2: 2-3, the total congestion rent value has been reduced from

Table 4.2: LMP at every bus considering losses

Bus no.	**Locational marginal price (LMP) in $/MWhr**	
	LP technique	**GA technique**
1	34.756	34.448
2	36.436	35.861
3	38.227	38.245
4	38.973	37.321
5	36.707	36.293
6	37.085	36.021
7	38.774	37.464
8	38.774	37.464
9	38.669	37.540
10	38.720	37.476
11	38.166	37.042
12	38.030	36.651
13	38.252	36.989
14	39.421	38.059

Table 4.3: Table for OPF with TCSC

Priority no.	**Congestion rent using TCSC**		**Generation cost using TCSC**	
	Total congestion rent ($/hr)	**TCSC place**	**Total generation cost ($/hr)**	**TCSC place**
1	638.34	Line 2: 2-3	8264.5	Line 1: 1-2
2	642.53	Line 3: 2-4	8291.2	Line 4: 1-5
3	687.31	Line 4: 1-5	8318.8	Line 3: 2-4
4	766.27	Line 1: 1-2	8355.5	Line 12: 7-9
5	803.96	Line 7: 4-5	8357.6	Line 6: 3-4
6	806.33	Line 5: 2-5	8407.5	Line 17: 9-14
7	812.34	Line 12: 7-9	8410.0	Line 2: 2-3
8	831.55	Line 6: 3-4	8411.0	Line 5: 2-5
9	852.53	Line 16: 6-13	8412.7	Line 16: 6-13
10	878.68	Line 17: 9-14	8414.1	Line 7: 4-5

874.72 $/MWhr to 638.34 $/MWhr. The former value has been calculated by DCOPF model using GA technique without TCSC and the later one after installing TCSC. As the value gets reduced, so this serves the purpose of managing congestion.

Table 4.4: LMP difference priority table

Priority no.	LMP difference ($/MWhr)	Priority location
1	2.9451	Line 4: 1-5
2	2.4929	Line 2: 2-3
3	2.1145	Line 1: 1-2
4	1.5531	Line 3: 2-4
5	1.0149	Line 17: 9-14

Table 4.5: Congestion rent contribution priority table

Priority no.	Congestion rent contribution (%)	Priority location
1	36.13	Line 1: 1-2
2	21.63	Line 4: 1-5
3	17.53	Line 2: 2-3
4	7.87	Line 3: 2-4
5	4.58	Line 7: 4-5

4.2 Test System 2: IEEE 30-Bus System

IEEE 30 bus system consists of 6 generators, 30 buses and 41 lines. In this case as there five generating units excluding the slack bus. Therefore, the value of GA parameter i.e., chromosome length has been taken as 60.

Table 4.6 shows the generated real power of all the generating units and the total generation cost while considering the losses. In this system also, it has been depicted that re-dispatch of generation using the GA technique results in substantial savings in the generation costs. The value of LMP at every bus is illustrated in Table 4.7.

The result for this test system is presented in Table 4.8 to 4.10. Table 4.8 shows the OPF results after TCSC placement for best ten locations to obtain minimum overall production cost and minimum overall congestion rent. In Table 4.8, it is shown that Line 5: 2-5, is the most optimal location in order to get minimum congestion rent i.e., 17.382 $/h. In a similar way, to obtain minimum production cost, the first optimal location is Line 5: 2-5. It has a total generation cost of 935.94 $/h. Now, these optimal locations should be confined by the employed methods. This will prove the efficacy of methods.

Depending on the difference of LMP values, best locations are shown in Table 4.9 for TCSC installation. Now, as the Table 4.8 shows that the best place to install TCSC is Line 5: 2-5, for both

Table 4.6: Generator real power considering losses

Gen. bus no.	**Generated power in MW**	
	LP technique	**GA technique**
1	80	81.542
2	80	75.350
5	50	43.242
8	17	38.916
11	30	25.721
13	40	36.294
Generation cost ($/hr)	984.36	953.98

the purposes. This line secures second place in LMP difference method priority list.

The best locations for TCSC installation, depending on the contribution of congestion rent are presented in Table 4.10. Now the Table 4.8 depicts that the best place to install TCSC for minimization of congestion rent and production cost is Line 5: 2-5. So, this line is present in the priority list of congestion rent contribution method. It secures first place in the priority list. Hence, it is concluded that both the methods are effective in locating the best lines for TCSC installation.

LMP difference method depicted Line 5: 2-5, on second place whether congestion rent method depicted it on the first place. Moreover, the later method is also capable in portraying the other optimal locations like Line 6: 2-6 and Line 1: 1-2. So, this proves the superiority of this method over the LMP difference method. After locating TCSC on Line 5: 2-5, the total congestion rent value has been reduced from 21.594 $/MWhr to 17.382 $/MWhr. The former value has been calculated by DCOPF model using GA technique without TCSC and the later one after installing TCSC. As the value gets reduced, so this serves the purpose of managing congestion.

It is not possible every time to place FACTS device at the most optimal location, so some another location should be searched as a substitute. The employed methodologies show the promising outcome for that cases.

Table 4.7: LMP at every bus considering losses

Bus no.	**Locational marginal price (LMP) in $/MWhr**	
	LP technique	**GA technique**
1	2.6000	2.6116
2	2.6756	2.6467
3	2.7375	2.6814
4	2.7739	2.6999
5	2.8143	2.7673
6	2.8083	2.7187
7	2.8318	2.7559
8	2.8203	2.7160
9	2.8112	2.7232
10	2.8127	2.7256
11	2.8112	2.7532
12	2.7498	2.6777
13	2.7498	2.6777
14	2.8127	2.7231
15	2.8388	2.7419
16	2.8078	2.7205
17	2.8227	2.7332
18	2.8853	2.7744
19	2.8948	2.7831
20	2.8790	2.7708
21	2.8479	2.7540
22	2.8501	2.7529
23	2.8822	2.7705
24	2.9015	2.7860
25	2.9064	2.7779
26	2.9831	2.8244
27	2.8619	2.7522
28	2.8332	2.7314
29	2.9610	2.8220
30	3.0106	2.8681

Table 4.8: Table for OPF with TCSC

Priority no.	**Congestion rent using TCSC**		**Generation cost using TCSC**	
	Total congestion rent ($/hr)	**TCSC place**	**Total generation cost ($/hr)**	**TCSC place**
1	17.382	Line 5: 2-5	935.94	Line 5: 2-5
2	18.174	Line 6: 2-6	937.95	Line 9: 6-7
3	18.685	Line 1: 1-2	939.34	Line 6: 2-6
4	19.262	Line 38: 27-30	940.82	Line 1: 1-2
5	19.570	Line 2: 1-3	951.01	Line 2: 1-3
6	19.758	Line 7: 4-6	951.47	Line 38: 27-30
7	21.062	Line 9: 6-7	952.24	Line 18: 12-15
8	21.930	Line 3: 2-4	969.81	Line 4: 3-4
9	22.578	Line 4: 3-4	971.15	Line 3: 2-4
10	22.930	Line 18: 12-15	971.81	Line 7: 4-6

Table 4.9: LMP difference priority table

Priority no.	**LMP difference ($/MWhr)**	**Priority location**
1	0.1158	Line 38: 27-30
2	0.1143	Line 5: 2-5
3	0.0799	Line 6: 2-6
4	0.0746	Line 2: 1-3
5	0.0697	Line 37: 27-29

Table 4.10: Congestion rent contribution priority table

Priority no.	**Congestion rent contribution (%)**	**Priority location**
1	19.76	Line 5: 2-5
2	13.77	Line 6: 2-6
3	9.65	Line 2: 1-3
4	7.19	Line 18: 12-15
5	6.84	Line 1: 1-2

Chapter 5

Conclusions and Future Work

5.1 Conclusions

Two methods namely, LMP difference method and congestion rent method have been implemented to deal with the problem of congestion in restructured power market. The employed methods are tested and validated on IEEE 14 and IEEE 30-bus test systems. These methods depend on the nodal prices or locational marginal prices. The analysis and calculation of marginal prices have been done using DC optimal power flow model. The techniques like linear programming and genetic algorithm have been employed for the DCOPF model. A comparative study is made between both the techniques, subsequently GA technique has been utilized to place FACTS device (TCSC) in the most optimal location. The following conclusions are drawn:

1. The results depict that both employed methodologies accurately confine the most optimal location for TCSC.
2. The superiority of congestion rent method is shown over the former one, as it not only comprises the LMP difference values but also the power flows of line.
3. Re-dispatch of generation using GA technique results in significant savings in the generation cost as compared to the LP technique.

5.2 Future Scope

The scope for the future work in the dissertation is recognized as:

1. The future work can take into account the reactive power and voltage magnitudes also. AC optimal power flow model can be used for the more precised results.

2. The algorithm can be extended to solve multi-objective optimization problems like improving voltage stability and transient stability along with the cost minimization in future.

3. Other FACTS devices like unified power flow controller (UPFC) and thyristor controlled phase angle regulator (TCPAR) can also be used for the congestion management purpose.

List of Publications

1. **International Conference**

   A. Sharma, "Locating series FACTS devices for managing transmission congestion in deregulated power market," communicated to *IEEE 7th Power India International Conference*, November 2016.

2. **International Journal**

   A. Sharma and S. K. Jain, "Allocating TCSC for congestion management in deregulated electricity markets" communicated to *IET Generation, Transmission and Distribution* (ISSN: 1751-8695, listed in SCI).

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Appendix A

Generator Data

A.1 Test System I: IEEE 14-Bus System

Table A.1: Cost Coefficients and Generator limits for IEEE 14-Bus

Genr. No.	Bus No.	a ($\$/MW^2hr$)	b (\$/MWhr)	c (\$/hr)	P_{max} (MW)	P_{min} (MW)
1	1	0.0430293	20	0	332.4	30
2	2	0.25	20	0	140	10
3	3	0.01	40	0	100	10
4	6	0.01	40	0	100	10
5	8	0.01	40	0	100	10

A.2 Test System II: IEEE 30-Bus System

Table A.2: Cost Coefficients and Generator limits for IEEE 30 Bus

Genr. No.	Bus No.	a ($\$/MW^2hr$)	b (\$/MWhr)	c (\$/hr)	P_{max} (MW)	P_{min} (MW)
1	1	0.00375	2.0000	0	80	15
2	2	0.01750	1.7500	0	80	15
3	5	0.06250	1.0000	0	50	10
4	8	0.00834	3.2500	0	55	10
5	11	0.02500	3.0000	0	30	5
6	13	0.02500	3.0000	0	40	10

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M.E (Power Systems)	Thapar University	Thapar University	9.39*

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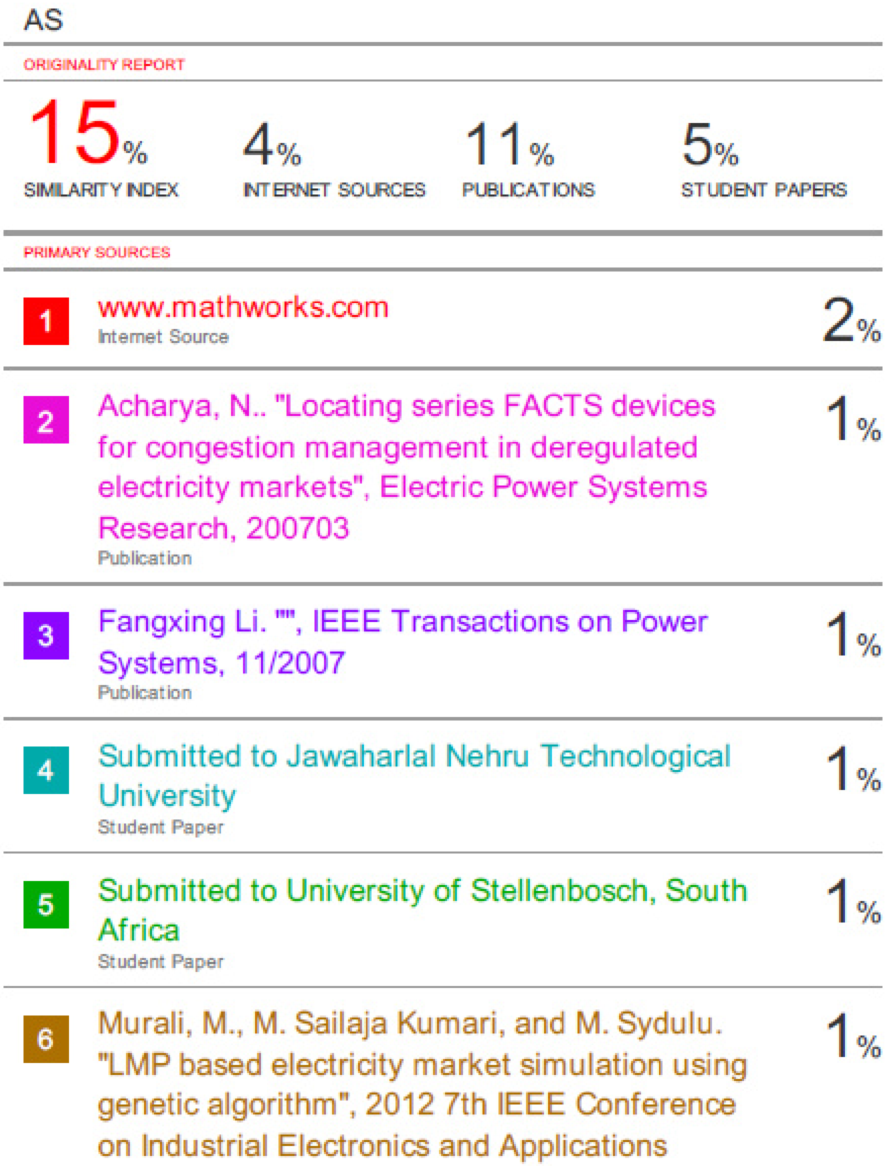

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