# CONGESTION MANAGEMENT IN DEREGULATED POWER SYSTEM

## THESIS

*Submitted in fulfillment of the requirement of the degree of*

**DOCTOR OF PHILOSOPHY**

*to*

***J. C.BOSE UNIVERSITY OF SCIENCE & TECHNOLOGY, YMCA, FARIDABAD***

*by*

**ANUBHA GAUTAM**

Registration No. YMCAUST/PH14/2011

***Under the Supervision of***

**Dr. P. R. SHARMA** **Dr. YOGENDRA KUMAR**

**PROFESSOR** **PROFESSOR**

**Electrical Engineering Department**

**Faculty of Engineering & Technology**

**J C Bose University of Science & Technology, YMCA**

**Sector-6, Mathura Road, Faridabad, Haryana, India**

**April 2022**

# DECLARATION

I hereby declare that this thesis entitled **CONGESTION MANAGEMENT IN DEREGULATED POWER SYSTEM** by **ANUBHA GAUTAM**, being submitted in fulfilment of the requirement for the Degree of Doctor of Philosophy in ELECTRICAL ENGINEERING under the Faculty of Engineering & Technology of J C Bose University of Science and Technology, YMCA , Faridabad, during the academic year 2021-2022, is a bona fide record of my original work carried out under guidance and supervision of **Dr. P. R. SHARMA, PROFESSOR, DEPARTMENT OF ELECTRICAL ENGINEERING**, J C Bose University of Science and Technology, YMCA, Faridabad, and **Dr. YOGENDRA KUMAR, PROFESSOR, DEPARTMENT OF ELECTRICAL ENGINEERING**, MANIT, Bhopal and has not been presented elsewhere.

I further declare that the thesis does not contain any part of any work which has been submitted for the award of any degree either in this university or any other university.

ANUBHA GAUTAM

YMCAUST/PH14/2011

# CERTIFICATE

This is to certify that this Thesis entitled **CONGESTION MANAGEMENT IN DEREGULATED POWER SYSTEM** by **ANUBHA GAUTAM**, submitted in fulfillment of the requirement for the Degree of Doctor of Philosophy in **ELECTRICAL ENGINEERING** under the Faculty of Engineering & Technology of J C Bose University of Science and Technology, YMCA, Faridabad, during the academic year 2021-2022, is a bonafide record of the work carried out under our guidance and supervision.

We further declare that to the best of our knowledge the thesis does not contain any part of any work which has been submitted for the award of any degree either in this university or any other university.

Dr. P. R. Sharma
Professor
Department of Electrical Engineering
J C Bose UST, YMCA
Faridabad

Dr. Yogendra Kumar
Professor
Department of Electrical Engineering
MANIT, Bhopal

Dated:

# ACKNOWLEDGEMENT

First of all, I sincerely acknowledge my gratitude to ***ALMIGHTY*** whose blessings have bestowed on me the willpower and confidence to carry out my project. It is both an elevating and humbling experience to have the opportunity to acknowledge all the people involved in this thesis work.

I have a great pleasure to express my deep sense of respect and sincere gratitude to my supervisor ***Dr. P. R. Sharma***, Professor, Electrical Engineering Department, J. C. Bose University of Science & Technology, YMCA, Faridabad, Haryana, and my co-supervisor ***Dr. Yogendra Kumar,*** Professor, Electrical Engineering Department, MANIT, Bhopal for their guidance, motivation, and inspiration. They have been my inspiration as I hurdle all the obstacles in the completion of this research work. Their encouragement and attention in every stage of my research work provided me with the spirit to complete this research.

I also wish to express my sincere gratitude to ***Dr. Poonam Singhal***, Chairperson, Electrical Engineering Department, J. C. Bose University of Science & Technology, YMCA, Faridabad, Haryana for her sincere help and for providing me with the necessary research facilities for the completion of the work.

I am very much thankful to ***Dr. Rajesh Kumar Ahuja***, Dean (Research and Development) J. C. Bose University of Science & Technology, YMCA, Faridabad, Haryana, who has been a constant support and inspiration to complete the research work.

I am also thankful to all faculty members and staff of the Electrical Engineering Department of J. C. Bose University of Science & Technology, YMCA, Faridabad for their continuous support and cooperation.

Though inept, I would like to express my deep gratitude to my ***parents*** for being supportive, understanding, patient, and for having shaped me into who I am. They have always encouraged my academic endeavour which is the greatest motivation in my study. I am grateful to my ***in-laws***, my ***siblings***, and all my ***family members*** for being a constant source of inspiration and support for me.

I also express my deep appreciation to my husband, ***Mr. Anurag Gautam,*** and my loving son ***Abhinav***, whose constant inspiration, patience, understanding, and moral support have greatly contributed to the realization of this work.

I feel indebted to all well-wishers, whose names remain unmentioned but who have never retraced back from helping me whenever the need arose.

ANUBHA GAUTAM
YMCAUST/PH14/2011

# ABSTRACT

The introduction of private sector market players in previously monopolistic power system and granting open access to grid has brought a change in the economic aspects of current deregulated power system. The deregulation has improved the quality of services to the society. Reliable and secure day to day power dispatch is one of the most important aspect that has to be seen by the system operator. Thus, there is a requirement of development of certain technologies and methodologies by the researchers so that the system operator may control different conditions that are faced during power transmission in deregulated environment.

Under the dominant deregulated power system environment, all the participating countries had adopted one or other types of deregulations, but the goal for this change is to create an economically friendly competition. To achieve this goal, the power system was divided into the companies which produces energy i.e., generation companies separated with the companies transmitting the power from sellers to the buyers. With the implementation of the deregulation a number of companies participated in generation and distribution. The interconnected transmission system aids effective and reliable power transmission securely to the customers with least number of power failures. The independent system operator applies some rules and regulations on open and non-discriminatory power transaction to make the competition healthy. The open access system helped the market participants to utilize the transmission facility to its maximum so as to cut the cost of laying down new transmission lines, but it also leads to some grave conditions when the system is not able to transmit desired power as some system safety constraint got violated. This condition is a serious hamper in the safety of system and is termed as congestion. Thus, the system operator has a crucial task to mitigate congestion. The congestion increases power losses in the system which results in significant deviation in system voltages. This results in reduction of Available Transfer Capacity and Security Margin of the system.

The congestion management methods can be broadly classified into two specific categories: 1) Preventive type and 2) corrective type. The preventive type congestion management deals with the prespecified line limits while the corrective type strategy amends the pre-defined limits to alleviate the congestion. With an increase in number of bilateral agreements signed between different market players for electricity trades, and with the likelihood of inadequate resources, the network may be subjected to an unavoidable congestion. Thus, here OPF framework is of acute importance to mitigate congestion.

In this research alleviating congestion involve enhancement of ATC, reduction of power loss, reduction in voltage deviation by applying TCSC and SVC. The location of FACTS devices is done with the help of sensitivity factors like LUF and DLUF. Further work is done by rescheduling the generators. The congestion management is carried out in three steps: (i) Generation rescheduling, (ii) Generation rescheduling with load curtailment and (iii) Using FACTS Devices. These three steps are carried out to ensure that the transmission system operates within permissible limits for the deregulated and restructured power system.

# TABLE OF CONTENT

**1.** Introduction

**2.** Literature review

**6.** Optimal rescheduling of generators to alleviate congestion using hybrid PSO-GWO

**7.** Conclusion and scope for future works

# LIST OF TABLES

# LIST OF FIGURES/ GRAPHS

# LIST OF ABBREVIATIONS

FACTS : Flexible AC transmission systems

TCSC : Thyristor Controlled Series Capacitor

SVC : Static Var Compensator

STATCOM : Static Synchronous Compensator

TCPST : Thyristor-Controlled Phase Shifting Transformer

SSSC : Static Synchronous Series Compensator

UPFC : Unified Power Flow Controller

TCPAR : Thyristor Controlled Phase Angle Regulators

GR : Generator Rescheduling

DG : Distributed Generation

SO : System Operator

GSF : Generator Sensitivity Factor

OPF : Optimal Power Flow

CM : Congestion Management

ATC : Available Transfer Capacity

NR : Newton Raphson

LUF : Line Utilization Factor

DLUF : Disparity Line Utilization Factor

PSO : Particle Swarm Optimization

GWO : Grey Wolf Optimization

RES : Renewable Energy Resources

LMP : Location Marginal Price

GA : Genetic Algorithm

BHA : Black Hole Algorithm

FA : Firefly Algorithm

PPI : Real Power Performance Index

POD : Power Oscillation Damper

IPFC : Interline Power Flow Controller

ALO : Ant Lion Optimization

EPS : Electrical Power System

AVR : Automatic Voltage Regulator

TRM : Transmission reliability Margin

CBM : Capacity benefit Margin

PTDF : Power Transfer Distribution Factor

ACPTDF : AC Power Transfer Distribution Factor

TPL : Total Power Loss

TQL : Total Reactive Power Loss

SM : Security Margin

VD : Voltage Deviation

$P_L$ : Active Power Loss

# CHAPTER I

# INTRODUCTION

## 1.1 BACKGROUND

The traditional power systems have been known as vertically integrated systems where the generation, power transmission, and distribution are handled by a solitary entity for a particular geographical location. This system was somewhat easier to coordinate as a whole of the functions have been controlled by a single operator. By considering the aim of the economy of services provided with reliable supplies, the vertically integrated utility had a technical objective of supplying good power quality only. The quality of power has been restricted to a constant voltage at a constant frequency. The reason for such a structure was to ensure the economic gains to the utility as the capital cost to set a generating unit was huge. The government invested in the power system and rules were implemented to provide services to a local area only. This helped the local utilities plan for expansion of the system with assurance to recover the amount invested without indulging in the unnecessary competition as far as the electricity rate has been concerned.

The government has implemented certain regulations which have to be followed by the electrical utilities to protect the consumers from unnecessary exploitation by the local bodies. Moreover, this helped the utilities to get support from the government for tackling certain problems such as the Right of Way for clearing land/corridor to lay down the transmission lines. Thus, the regulations for electricity were intended only for protecting the consumers from exploitation and to recover the expenditure as capital and operational cost.

## 1.2 MOTIVATION

In a vertically arranged power utility every part of the utility i.e. generation, transmission and distribution were under the same utility. The electricity was provided to the consumers without any discrimination of profit and loss. In due course of time with increased population and enhanced industrial growth, there was a need for enhanced power generation and transmission. The single utility was not able to generate the required revenue to generate extra power. Then deregulation was brought to the power system with the main objectives of:

a) To provide electricity for all reasonable demands.

b) To encourage competition in the generation and supply of electricity.

c) To improve the continuity of supply and the quality of services.

d) To promote the efficiency and economy of the power system.

With the participation of private generators and utilization of pre-existing transmission structures, the lines are utilized hitting their thermal and voltage limits. This resulted in large system losses, reduced voltage margin to work with, lower stability, and decreased security margin. These all effects the power economics and social welfare. Thus, there is a valid requirement to work on the methods to improve system efficiency together with social welfare. In literature, a lot of work is done on different methods to decrease congestion. Both cost-free and non-cost-free methods to mitigate congestion have been implemented on the system. Most of the methods are not economical but are quite effective to manage congestion. Some of the methods are economical but not very efficient to mitigate congestion. These conditions are studied and considered to be applied for a better solution to the congestion management problem. Different algorithms have been applied to make the solution to congestion more economic and efficient.

## 1.3 NEED FOR DEREGULATION

The need for liberalization or in other words deregulation came into existence due to some major concerns aroused due to population growth and the industrial revolution. In the late nineties, some countries like the UK, Norway, Sweden, Finland, and some parts of the US felt the need for deregulation to supply huge expansion of loads and dissatisfaction of customers due to irrational electricity prices. Thus, deregulation has been introduced in the abovesaid countries for the following reasons:

### 1.3.1 Need for Amendments in Regulation

The original need for regulation was to give a competition-free environment for the utilities to expand and to recover the initial capital cost invested. The power system framework once developed, only required the operational charges to be recovered in the form of electricity consumption charges from the end-users. These charges have been taken from the customers for so long time that at the starting of the 21st Century, the utilities have recovered the finance government has invested. The collection has reached that amount that after taking the profit out the remaining was reinvested in the expansion of the power system. Also, with time the technology has developed new tools and techniques which made the system approximately risk-free to be invested. Electricity has been treated like a commodity that can be purchased at any time from the market with variable rates following the availability. Thus, the necessity of the regulations for governing the power system by the electrical utilities has been absconded.

### 1.3.2 Accepting Private Investments

As time passed, with liberalization private investors have been invited to participate in the generation. The reason for such implication is the exponential expansion of loads and deficiency of finance with the government. The power system cannot be expanded to match the pace of development as it requires a lot of finance. Thus, private generators and nearby load centers have been invited for investment. The idea for such participation came from the technological development of modern industries governed by the private sector.

### 1.3.3 Development of Advanced Technology

With the development of new cutting-edge technology, the way to think about power system development and customer interaction has changed a lot. The invention of new power electronics devices had made the power sector grow but with the involvement of the private sector. This was not possible with the involvement of the government sector only due to the policies made with a different objective and mode of operation to achieve it. Technological developments had made the regulated power system obsolete.

### 1.3.4 Vision Towards Customer

The traditional regulated power system responded to a customer only when the customer reached the utility, after going through the details provided by him. This took a long time to settle down the needs of the customer. Here the customer has not been classified as a promising profit-giving customer or a normal customer. Every customer has been seen as the same. But with technological development, the changing demand of customers has been seen and judged in advance to give him the desired service with higher gains in return. This way of seeing and treating the customer has started a new trend of deregulation.

## 1.4 MAIN CONCEPTS OF DEREGULATION

The deregulation in the power system is unbundling of the regulated power system entities. So, in the deregulated environment the generation, transmission, and distribution become separate entities named Genco, Transco, and Disco. Two more entities have been introduced called Independent System Operator (ISO) and retailers (RESCO). ISO has a role to keep an eye on all transactions taking place among the entities of the deregulated power system. Retailers keep track of consumer demand. Consumer purchases electricity from these retailers which in turn get energy from Genco. The charges for electricity in a regulated market comprised of generation and transmission both as a single bill but in deregulated power system the customer has to pay the charges of electricity consumption which constitutes: Charge of electricity units, Wheeling charges for using the transmission system, frequency, and voltage regulation charges and penalties on low power factor. These may or may not be reflected in the bills but are included in them and has to be paid by the consumer. The deregulated power system transactions can be explained by Figure1.1 where the function of ISO can be detailed as an independent authority that does neither own any generation company nor have a distribution company but keeps an eye on each transaction that is done among the entities. ISO is an entity assigned with the accountability of safeguarding dependability and power system security.

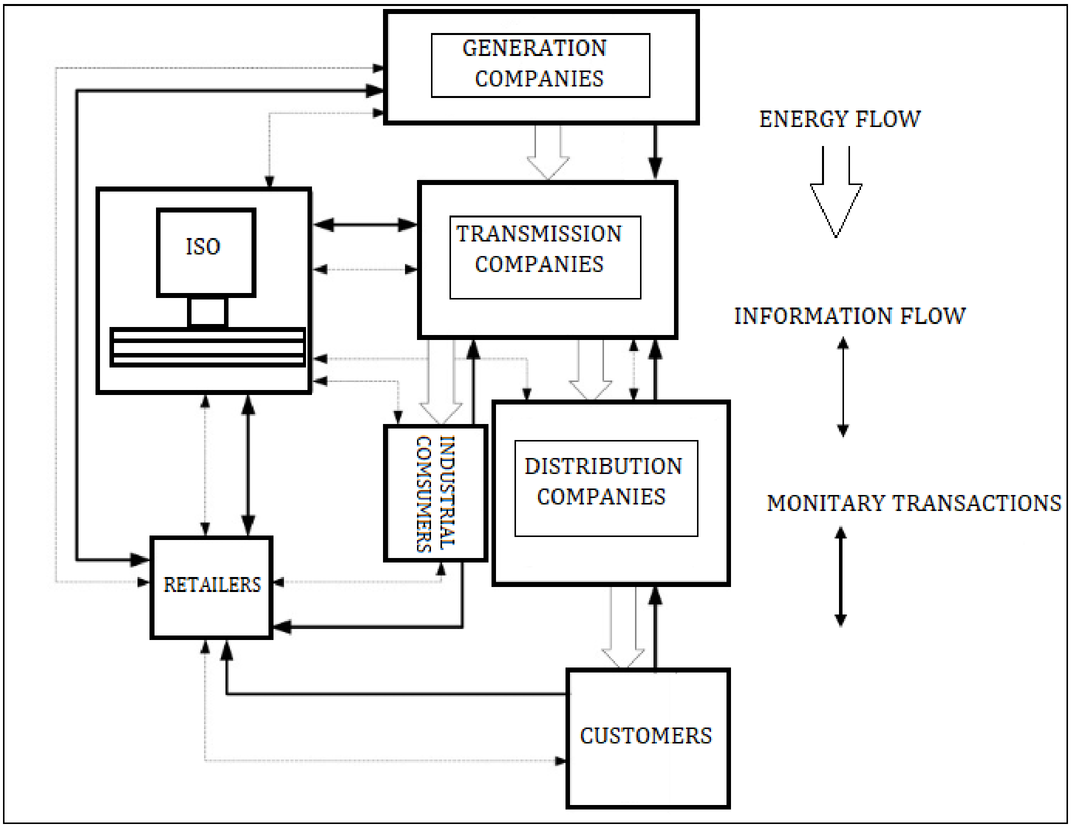

**Figure 1.1 Deregulated power system**

It is an independent authority and does not participate in the electricity market trades has some reserve power capacity to be used at the time of contingency. The deregulated power system is beneficial in the following ways:

a) The capacity of the system increases manifold.
b) There is no irrational pricing. This makes the system more distinct and trustworthy.
c) Due to the introduction of competition the investors will bring new cutting-edge technology which in turn is beneficial to the end-user in terms of power quality as well as power economics.

d) As there is reserve sharing between two interconnected areas, the cost of ancillary service is reduced. This will increase the availability of power at comparatively lower rates.
e) Surplus power can be transferred from power deficient areas at a lower cost and with the least disturbance to the interconnected system.

## 1.5 IMPLEMENTATION OF DEREGULATION

The reforms took place in three phases:

### 1.5.1 Phase I

This phase started in 1991 when the Indian economy was facing its worst days so the investment in the power system could not be planned in the budget. Thus, SEB regulations were reformed for the first time and private investors in a generation were invited. This invitation was with a guaranteed profit for the investors. This reform was not very successful as the bond between SEB's and private investors was too long and was not feasible for the poor financial condition of SEBs. In 1995 Government again reformed the policies with several add-on facilities for the private generators of capacity more than 1000MW like tax holiday for 10 years, custom duty exemption, etc. for enhancing the power quality. But failed again due to the financial crisis of SEB's [1]-[3].

### 1.5.2 Phase II

After phase –I was unsuccessful, phase –II for reforms was launched with the following add-on regulations in the Electricity ACT 1998 [1]-[3].

a) State and central transmission utilities were introduced into the power system in 1998 to sustain and lay down of new power transmission network.
b) State and Central Regulatory Commission was set up by the Electricity Regulatory Commissions Act 1998.
**c)** Financial support to State Electricity boards and new distribution reforms was promoted under the "Accelerated Power Development & Reform Program" in February 2001.

### 1.5.3 Phase-III

This phase, categorized by the Electricity Act, 2003, replaced the previous three Acts i.e. Indian Electricity Act-1910, Act-1948, and the Electricity Regulatory Commissions Act, 1998 [1]-[3]. In this ACT, three major practices have been considered to reform previous ACTs.

a) The distribution sector opened for the private market players to introduce a healthy competitive environment in the field of distribution through previously provided open access channels.
b) Local generation of power has been fostered, where excess generation can be shared with the grid.
c) The SEB's were unbundled and three separate entities evolved named GENCOs (the companies dealing with generation only), DISCOs (the companies involved in distribution only), and the TRANSCOs (the companies transmitting power from generators to distributors).

Other than above- mentioned features, Electricity Act 2003 also included

a) Increased competition in the electricity markets.
b) Protection of Interests of Consumers
c) Electrification of rural areas.
d) Irrational tariffs were eliminated and rationalization of electricity tariffs was introduced.
e) Delicensing in generation.

## 1.6 EFFECTS OF DEREGULATION ON POWER SYSTEM

Power system deregulation is widely adopted throughout the world, despite difficult targets set for its efficient application. The policies have been made for highly efficient power development programs, keeping in mind the problems faced during optimization of the system and reliable operation within rationalized acceptable electricity prices [4]. The implementation of deregulation policies may result in some risks and unwanted effects on the system which may be summarised as below:

a) The prices of electricity may not drop as predicted before implementing deregulation. Some more charges are added up in the form of wheeling charges, administrative charges, reactive power control charges, and voltage and frequency control charges.
b) The competitive markets in deregulation may sometimes are not beneficial for the customer though companies may be benefited. The price competition may result in bad power quality as this may benefit the energy player but is not good for the customer.
c) In technologically backward countries, the energy supplied in the deregulated system may not be secure and reliable. This happens when there is a lack of skilled labour in the energy industry.
d) Big companies are always controlling markets and forming syndicates. This happens in the power sector too. Few big energy corporations control the market and are involved in price rigging to collect high charges from customers and to earn profits over the cost of services.
e) The utilization of pre-existing transmission networks by the private energy players resulted in the overloading of lines. With the deregulations and participation of private generators, the pre-existing transmission lines are heavily loaded. The lines are continuously working at their thermal and voltage limits. The condition which results in the inability of lines to transmit the demanded power is termed congestion. Congestion in extreme cases can cause severe damage to the system [5],[6].

## 1.7 CONGESTION

Deregulation together with advantages has brought certain detriments to the power system. One of the minuses is congestion in the system. Congestion is a major technical problem expected to occur in the vertically aligned system as well as in the horizontally aligned power system. Congestion if continue to persist in the system can cause disturbances and when reaches its severe case may also lead to a system outage. Thus, congestion not only has been a menace to the system instruments but also leads to inferiority in power quality [7]. The ill effects of congestion may be summarised below:

a) System disturbances when not treated timely in extreme cases may lead to system failure.
b) The instruments and equipment which are incorporated into the system may be destructed due to congestion which may result in a severe breach of system security.
c) The system may become less reliable when power quality is concerned.
d) Power system economics is reduced as a significant amount of power is lost in transmission. This also adversely affects system efficiency.
e) Severe socio-economic consequences may have to be faced due to frequent blackouts which are the result of congestion.
f) The consumer has to pay irrational prices for limited stocks.
g) All existing resources cannot be a participant in the generation hence resulting in loss of resources and increment of tariffs.

The points above show that congestion must be mitigated so that system may work efficiently and reliably.

### 1.7.1 Methods to Mitigate Congestion

For mitigating congestion, numerous methods have been suggested in the literature. Congestion management can be done by considering the operational cost of the system. Based on the operational cost the technique may be cost-free (with no impact on operational cost) and non-cost-free (includes impact on operational cost). These methods are applied to the three sections of the power system i.e., generation, transmission and distribution.  Cost-free methods are also called technical methods which include phase shifting or tap changing of transformers. The cost-free methods are at the retention of the transmission system operator (TSO). While applying tap changing transformer or FACTS device only operational cost is considered for the research work and the capital cost is considered nominal [8]. Out of these two methods, the FACTS application is the most widely used method for managing congestion [9], [10]. FACTS devices are very versatile instruments that can be implemented in various contingency conditions. These devices can be used in series to the transmission line, between two buses, or on the buses as shunt devices and can also be implemented in a combined series and shunt form. Other methods of congestion management are non-technical methods that impact operational costs. Generation Rescheduling (GR) [11], Distributed Generation (DG) [12], curtailment of load [13], and nodal pricing-based methods are categorized under non-technical methods.

#### 1.7.1.1 Technical Methods to Mitigate Congestion

#### A) FACTS Devices

Using FACTS devices is the most traditional method of mitigating congestion. These may be series, shunt, or compound types. Figure1.2 presents the classification of FACTS devices. FACTS may be categorized based on location and type of FACTS controller used. Based on the position and connection in the system, the FACTS can be classified into three major categories:

a) Shunt devices like static synchronous compensator (STATCOM) and Static VAR compensator (SVC). These devices have been used at places in the power system where there is a need to control voltage magnitude and reactive power flow.

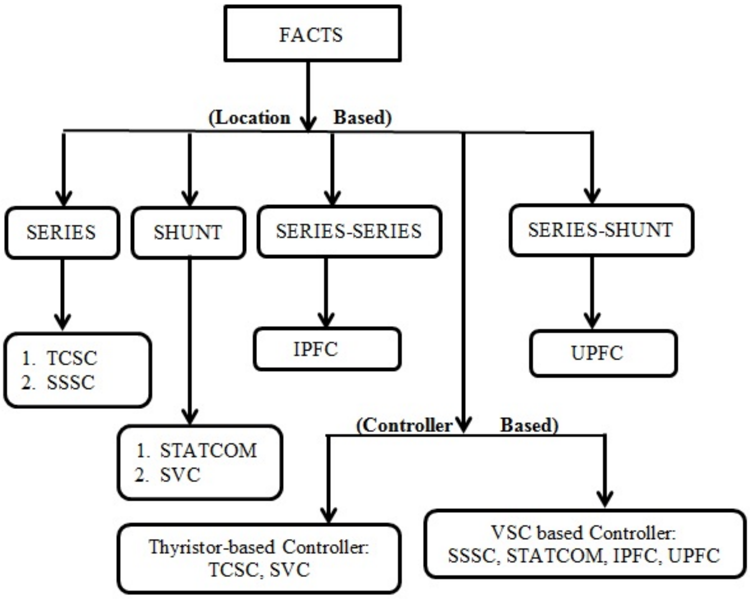

**Figure 1.2 Classification of FACTS devices**

b) For improving real power flow, improving transient stability, and damping out power oscillations the second category of FACTS devices, Series FACTS devices, such as Static Synchronous Series Compensator (SSSC), Thyristor-controlled phase-shifting transformer (TCPST), and Thyristor-controlled series capacitor (TCSC) have been implemented.

c) FACTS devices like Unified Power Flow Controller (UPFC), constitute both series and shunt devices. These types of devices are quite versatile as perform functions of both series and shunt FACTS devices.

Thus, we can see that some FACTS devices help in reactive power compensation/flow control, voltage control, and hence maintaining voltage profile for voltage stability, active power flow control/compensation, and improvement of transient stability by power system oscillation damping [14]. The FACTS devices and their modeling can be expressed in the next sub-sections.

### A.1 Thyristor Controlled Reactor (TCR):

The circuit diagram for TCR is shown in Figure 1.3. The thyristors being the basic controlling elements are connected anti-parallel to each other and their combination is in series with the reactor.

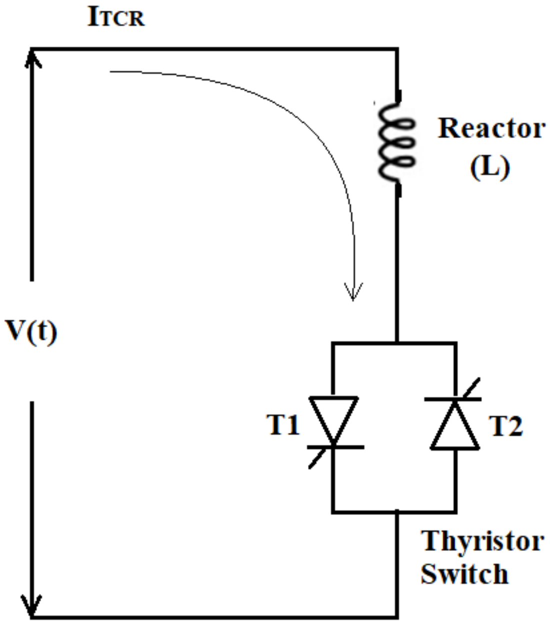

**Figure 1.3 Elementary TCR**

In TCR, the thyristor controller acts as a switch for the linear reactor to aid the reactor to work as a regulated inductive susceptance. Here, susceptance is a function of the firing angle, θ. However, leaving the condition of full conduction, the working of TCR introduces harmonic distortions hence there is a further requirement to filter the harmonics. The relation between firing angle and conduction angle of the two thyristors can be written as:

$$\sigma = 2(\pi - \theta)$$

With the applied voltage, $v(t) = \sqrt{2}\, v\ Sin\omega t$

The instantaneous current, $I_{TCR}$ can be given by:

$$I_{TCR} = \frac{1}{L}\int_{\theta}^{\omega t} \sqrt{2}\, v\ Sin\omega t\ dt$$

$$i_{TCR} = \frac{\sqrt{2}v}{\omega L}(cos\theta - cos\omega t) \qquad \forall\ \theta \le \omega t \le (\theta + \sigma) \tag{1.1}$$

Writing Fourier expression for equation (1.1):

$$i_{TCR} = \frac{V}{j\omega L\pi}[2(\pi - \theta) + \sin 2\theta] \tag{1.2}$$

From equation (1.2) the susceptance value can be well predicted as a function of controllable parameter θ:

$$i_{TCR} = -jB_{TCR}\, v \tag{1.3}$$

here,

$$B_{TCR} = \frac{2(\pi-\theta)+\sin 2\theta}{\omega L\pi} \tag{1.4}$$

### A.2 Thyristor Controlled Series Capacitor (TCSC)

The basic model of TCSC connected to a line between bus i and bus j is shown in Figure1.4.

The TCSC uses a low-cost series capacitor to provide adjustable series reactance (capacitive). TCSC is quite widely used due to the following:

- TCSC Continuously controls line series compensation level.
- Dynamically control the flow of power in a specific line in the network for OPF.
- Reduction of the level of sub-synchronous oscillations.
- Decreases dc-offset voltages and supports voltage levels in the system.
- During the flow of large short-circuit currents, the TCSC can shift to the variable inductance from the variable capacitance mode, and reduce the value of short circuit currents to a safe value.

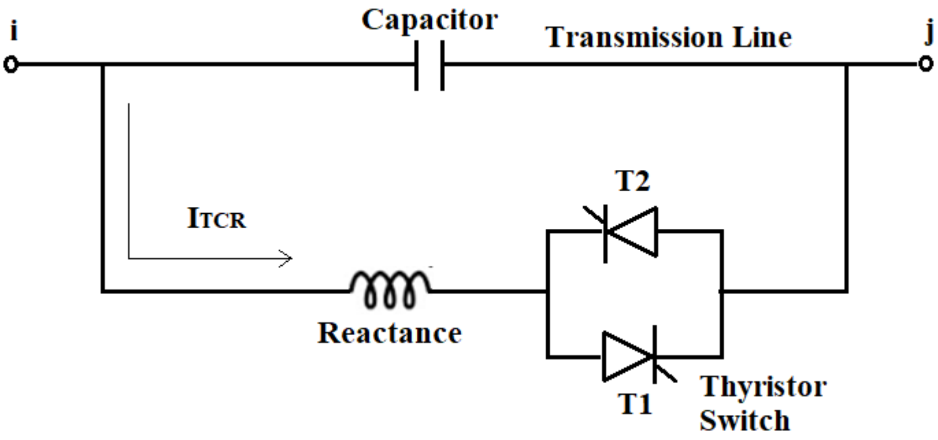

**Figure 1.4 TCSC model**

The basic principle of operation of TCSC includes the manipulation of circuit impedance and hence the impedance of the transmission line to which it is connected. The equivalent impedance of the line with TCSC connected to it can be formulated as:

$$Z_{eq} = \left(\frac{j}{(\omega C)}\right) || (j\omega L)$$

$$Z_{eq} = \left(\frac{-j}{(\omega C-\frac{1}{\omega L}}\right) \tag{1.5}$$

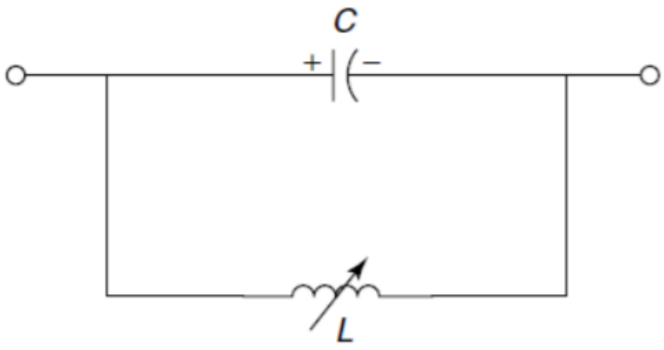

**Figure 1.5 A fixed capacitor with a variable inductor**

From equation (1.5):

If $\left(\omega C - \frac{1}{\omega L}\right) > 0$ then the circuit provides variable capacitive reactance.

If $\left(\omega C - \frac{1}{\omega L}\right) < 0$ then the circuit provides variable inductive reactance.

The TCSC is approximately similar in working to that of a parallel combination of L & C. But with a difference the parallel LC circuit deals with only sinusoidal supplies while the parallel LC in the case of TCSC as shown in Figure1.5, with fixed capacitor and thyristor-controlled inductor deals with non-sinusoidal waveforms due to switching operation of thyristors. TCSC works in three fundamental modes:

### A.2.1 Bypassed Thyristor Mode

The thyristor bypass mode is shown in Figure1.6. In this mode of operation, the thyristors are in full conduction mode. The conduction angle is $180^0$. To make TCSC work in this mode thyristors are fired exactly when thyristor voltage becomes positive after reaching the zero value. This results in a constant current through the thyristors. Here TCSC is acting as a parallel LC arrangement. Here the nature of module current will be inductive, where the reactive susceptance is greater than the capacitive reactance.

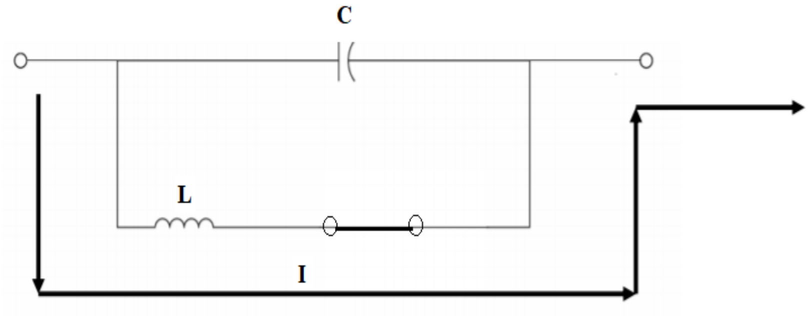

**Figure 1.6 TCSC in thyristor bypass mode**

### A.2.2 Blocked Thyristor Mode

This is called the waiting mode. Here the firing pulses are blocked to turn off the thyristor as shown in Figure 1.7. If blocking of firing pulse is done when the thyristors are conducting, the thyristors turn off as soon as the current becomes zero through them.

The TCSC circuit reactance here is capacitive so it behaves like a fixed-series capacitor.

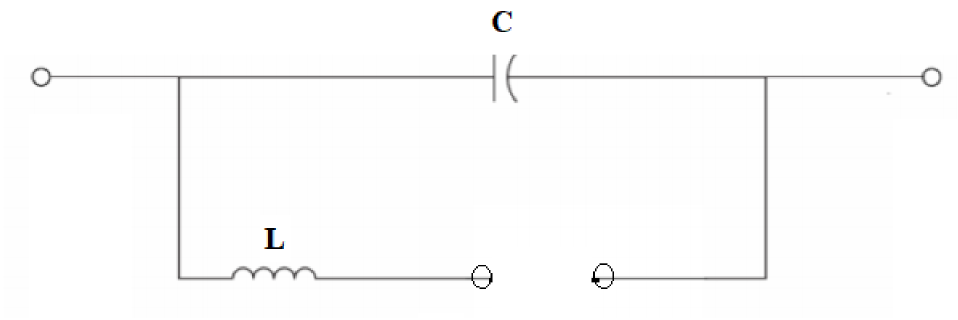

**Figure 1.7 Blocked thyristor mode of TCSC**

Here the capacitive dc-offset voltages are under observation and the same are settled quickly so that no harm is caused to the transformers of the transmission system.

### A.2.3 Partly Conducting Thyristor or Vernier Mode

This mode is realized by varying the firing angles of two thyristors in the prescribed limits. In this mode of operation controlled fixed capacitive reactance and/ or variable inductive reactance are obtained. This mode again is divided into two more types.

- ***Capacitive -Vernier control mode***: In this mode of operation the thyristors are fired exactly when voltage and current across the capacitor have opposite polarities.

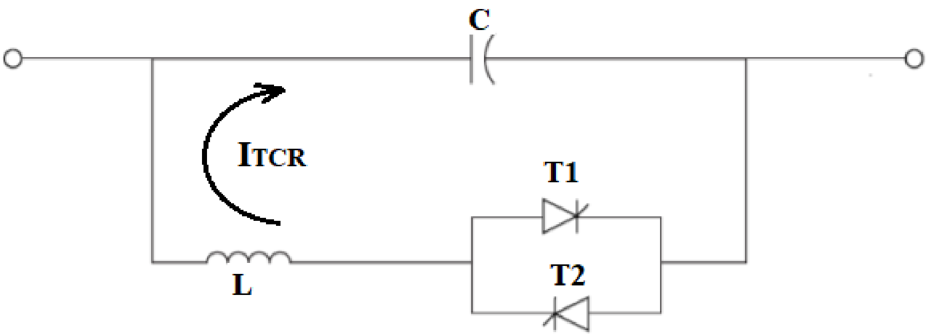

**Figure 1.8 Capacitive- Vernier control mode**

As shown in Figure 1.8 the direction of TCR current is opposite to that of capacitor current, resulting in a loop TCSC controller current. This loop current when flows through the capacitor, increases the voltage across it and thereby provides the series compensation. The maximum TCSC reactance, in this case, is 2.5 to 3 times the capacitive reactance at $\theta = \theta_m$ where $\theta$ is the firing angle of the thyristor.

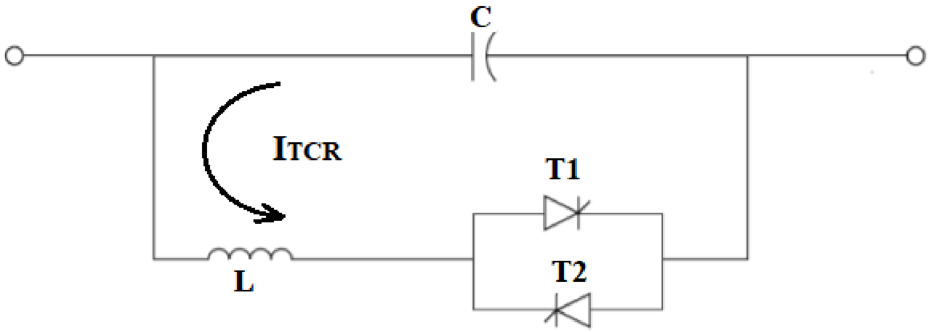

**Figure 1.9 Inductive -Vernier mode**

- *Inductive -Vernier mode:* This mode represents a high-level thyristor conduction mode where the direction of TCSC controller current reverses and the net TCSC impedance is inductive as shown in Figure1.9.

From the above discussion it is clear that TCSC can be modeled in two ways:

1) Variable reactance model
2) Firing angle model.

In this research work, TCSC is modeled as variable reactance. This model assumes a continuous reactance change availability.

### A.3 Static VAR Compensator (SVC)

Figure 1.10 shows the basic circuit diagram of SVC. The is a shunt device of the FACTS family which is applied to control power flow and improve the transient stability of the system. The main function of SVC is to maintain system voltage by the control of reactive power injected into the system or supplied from the system. When due to contingencies system voltage raises from a predefined value, SVC absorbs reactive power. On the other hand, with reduced voltage levels of the system, SVC generates and injects reactive power into the system.

SVC devices cannot be operated at normal line voltage levels hence these are connected to the transmission line with the help of a stepdown transformer as shown in Figure1.11, so it can work on reduced voltage levels. These reduced voltage levels reduce the size and rating of the compensator even though the size of conductors is increased to deal with the enhanced levels of currents due to the decreased voltage levels.

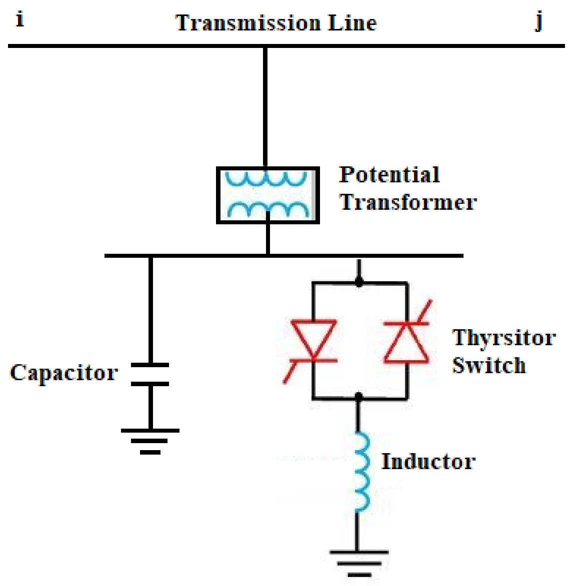

Figure 1.10 SVC Circuit

. An SVC operates by two methods:

- As a voltage regulator for adjusting the voltage within the pre-defined values.
- As reactive power regulator to maintain the susceptance value of the device at a constant value.

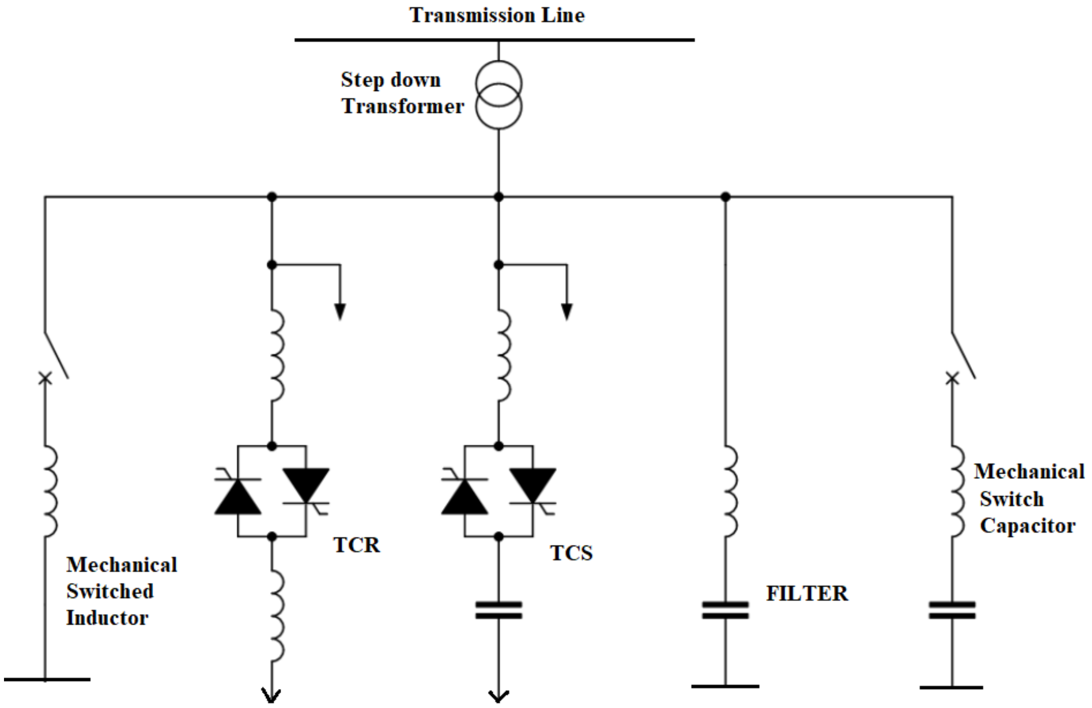

Figure 1.11 Schematic of SVC

When the susceptance value of the system remains at a value within the prescribed limits decided by the reactive power of the capacitors and reactors, the voltage remains at a controlled value and is termed a reference voltage. Voltage reduction takes place which ranges between 1 to 4 % when there is a heavy demand for reactive power at the load end. The VI characteristic is shown in Figure1.12.

$V = V_{ref} + X_s * I$ $\forall$ values of susceptance lying between maximum values of $B_c$ and $B_l$

$$V = -\frac{I}{B_{cmax}} \quad \forall \quad B = B_{cmax} \tag{1.6}$$

$$V = \frac{I}{B_{cmax}} \quad \forall \quad B = B_{lmax} \tag{1.7}$$

There are some advantages with SVC installed in the system:

- The power transmitting capacity of the line is increased.
- The transient stability of the system is enhanced.
- Enhances steady-state stability where there is a large fluctuation of voltages.
- Load power rating is enhanced thus power losses are reduced significantly.

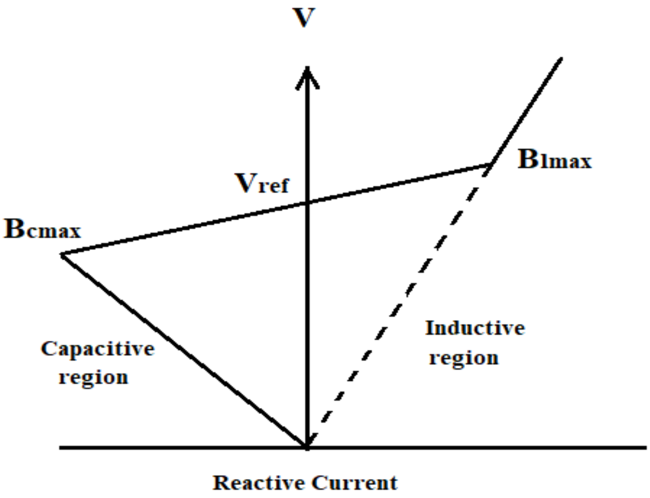

**Figure 1.12 VI Characteristics of SVC**

With the above-mentioned advantages SVC has certain disadvantages also:

- For surge impedance compensation additional equipment is required.

- Not suitable for furnace loading.
- Heavy size.

### A.4 Solid State Series Compensator (SSSC)

SSSC works more or less similar to static phase shifters i.e., it regulates active power flow by injecting voltage in the line in quadrature with the line voltage to maintain the steady-state operation of the system. But the SSSC is a very adaptable controller as compared to the phase shifter. The reason for no reactive power withdrawal by SSSC from the AC system to which it is connected is because it has a DC capacitor that supplies the reactive power demand of SSSC during the operation. This distinguishing property of SSSC makes it proficient in regulating both reactive and active power and hence the magnitude of nodal voltage. The basic connection diagram of SSSC in a line is debriefed in Figure1.13.

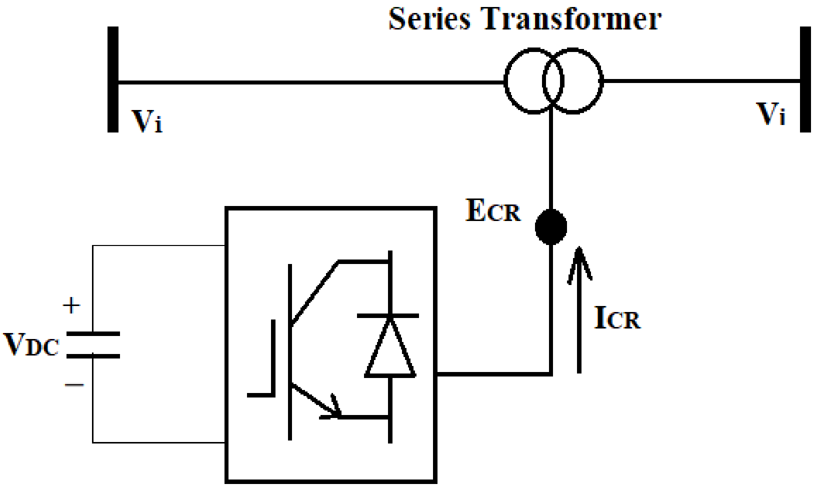

**Figure 1.13 Basic schematics of SSSC**

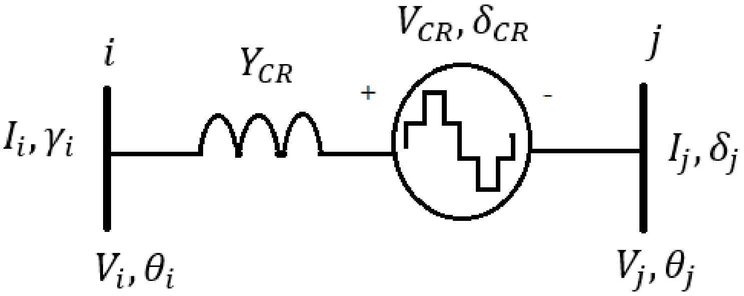

**Figure 1.14 Voltage source representation of SSSC in solid-state**

A suitable iterative algorithm is applied to get the phase angle and magnitude of the given SSSC model to give a specified value of reactive and real power flows. The maximum and minimum limits of the magnitude of voltage, $V_{CR}$, depend on the capacitor rating of SSSC. Voltage phase angle $\delta_{CR}$ takes any value between 0 and 2 radians. The transfer admittance equation can be written as:

$$\begin{bmatrix} I_i \\ I_j \end{bmatrix} = \begin{bmatrix} Y_{CR} & -Y_{CR} & -Y_{CR} \\ -Y_{CR} & Y_{CR} & Y_{CR} \end{bmatrix} \begin{bmatrix} V_i \\ V_j \\ E_{CR} \end{bmatrix} \tag{1.8}$$

here,

$$I_j = \left[I_j^a, \gamma_j^a \quad I_j^b, \gamma_j^b \quad I_j^c, \gamma_j^c\right]^t \tag{1.9}$$

$$V_j = \left[V_j^a, \theta_j^a \quad V_j^b, \theta_j^b \quad V_j^c, \theta_j^c\right]^t \tag{1.10}$$

$$E_{CR} = \left[V_{CR}^a, \delta_{CR}^a \quad V_{CR}^b, \delta_{CR}^b \quad V_{CR}^c, \delta_{CR}^c\right]^t \tag{1.11}$$

$$Y_{CR} = \begin{bmatrix} Y_{CRi}^a & 0 & 0 \\ 0 & Y_{CRi}^b & 0 \\ 0 & 0 & Y_{CRi}^c \end{bmatrix} \tag{1.12}$$

### A.5. Unified Power Flow Controller

A UPFC can be considered made of two voltage source converters with a shared capacitor on their DC side and an integrated controller circuit.

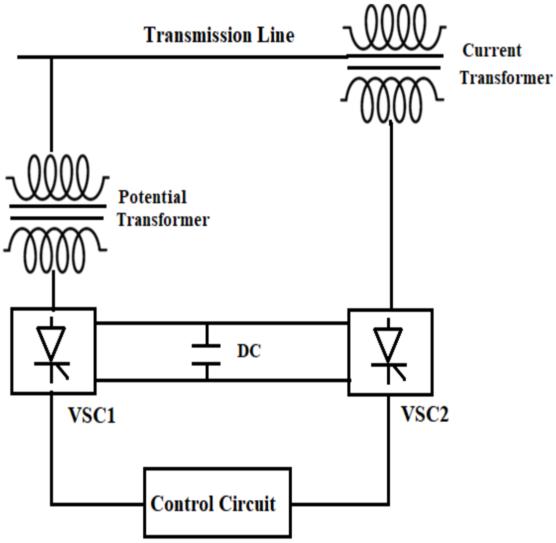

**Figure 1.15 UPFC circuit**

A schematic and corresponding circuit diagram of UPFC is shown in Figure 1.15. UPFC controls real and reactive power flow with voltage magnitude simultaneously. The controller may control one of the parameters or more than one parameter or none of the parameters as per the requirement of time. Figure1.16 shows an equivalent circuit with a solid-state voltage source representation of UPFC. The shunt converter supplies the active power demanded by the series converter after drawing it from the AC network. This active power is supplied to bus j through the DC link.

The nodal voltage at bus j is incremented as the output voltage at terminals of the series converter is added to it. The strategy of power flow control is determined by the magnitude of phase angle i.e., $\delta_{CR}$ while the voltage regulation is offered by the value of output voltage $E_{CR}$.

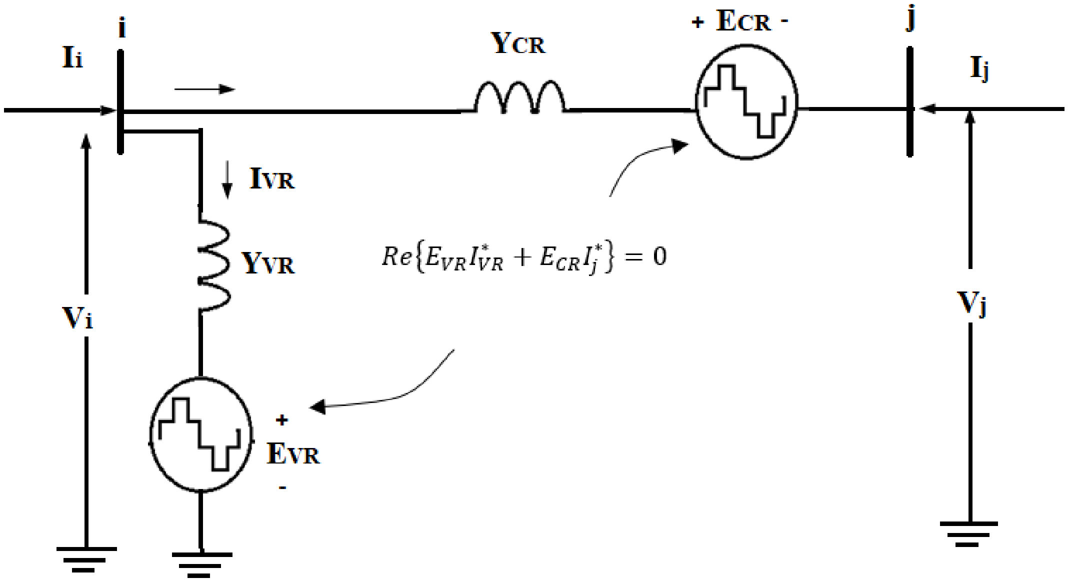

**Figure 1.16 Equivalent circuit for UPFC based on solid-state source**

The shunt converter provides independent voltage regulation by either absorbing or generating reactive power, at the location of its connection with the system. The shunt converter also facilitates the exchange of real power between the series converter and AC systems.

Figure 1.16. shows the shunt and series-connected solid-state voltage source, $E_{VR}$ and $E_{CR}$ respectively with a real power equation linking the two sources. The shunt voltage source is coupled to the AC line via a potential transformer while the series-connected voltage source is connected with the help of a current transformer. Mathematically the

voltage sources and constrained real power equation connecting the two voltage sources can be represented as,

$$E_{VR}^{\rho} = V_{VR}^{\rho}(cos\delta_{VR}^{\rho} + jsin\delta_{VR}^{\rho}) \tag{1.13}$$

$$E_{CR}^{\rho} = V_{CR}^{\rho}(cos\delta_{CR}^{\rho} + jsin\delta_{CR}^{\rho}) \tag{1.14}$$

$$Re\left\{-E_{VR}^{\rho}I_{VR}^{*\rho} + E_{VR}^{\rho}I_{j}^{*\rho}\right\} = 0 \tag{1.15}$$

In equations (1.13), (1.14), and (1.15) ‘ρ’ represents the three-phase quantities i.e., phase a phase b, and phase c. Now the transfer matrix equation can be written as (referring to Figure 1.16):

$$\begin{bmatrix} I_i \\ I_j \end{bmatrix} = \begin{bmatrix} (Y_{CR} + Y_{VR}) & -Y_{CR} & -Y_{CR} & -Y_{VR} \\ -Y_{CR} & Y_{CR} & Y_{CR} & 0 \end{bmatrix} \begin{bmatrix} V_i \\ V_j \\ E_{CR} \\ E_{VR} \end{bmatrix} \tag{1.16}$$

### A.6 Static Compensator (STATCOM)

The STATCOM constitutes a VSC connected to the transmission line through a shunt-connected transformer as shown in Figure1.17. It is the stationary complement of the rotating synchronous condenser. It is different from a synchronous condenser in a way that it has no moving part so it can generate or absorbs reactive power at a higher rate. Principally, it performs the voltage regulation function in the same way as the SVC but is much more efficient as its functioning is not by the existence of low voltages. Figure1.18 shows the solid-state voltage source equivalent of the STATCOM-connected system. The voltage source (shunt) of the three-phase STATCOM may be denoted mathematically as:

$$E_{VR}^{\rho} = V_{VR}^{\rho}\left(cos_{VR}^{\rho} + jsin\ \delta_{VR}^{\rho}\right) \tag{1.17}$$

Here ρ represents three-phase quantities a, b and c.

The maximum and minimum values of voltage magnitude depend on the capacitor rating of STATCOM. The value of $\delta_{VR}^{\rho}$ may vary from 0 to $2\pi$ radians. Referring to Figure1.18 the transfer admittance equation of STATCOM can be written as:

$$[I_J] = [Y_{VR} - Y_{VR}]\begin{bmatrix} V_j \\ E_{VR} \end{bmatrix} \tag{1.18}$$

Here,

$$I_j = \left[I_j^a, \gamma_j^a \;\; I_j^b, \gamma_j^b \;\; I_j^c, \gamma_j^c\right]^t \tag{1.19}$$

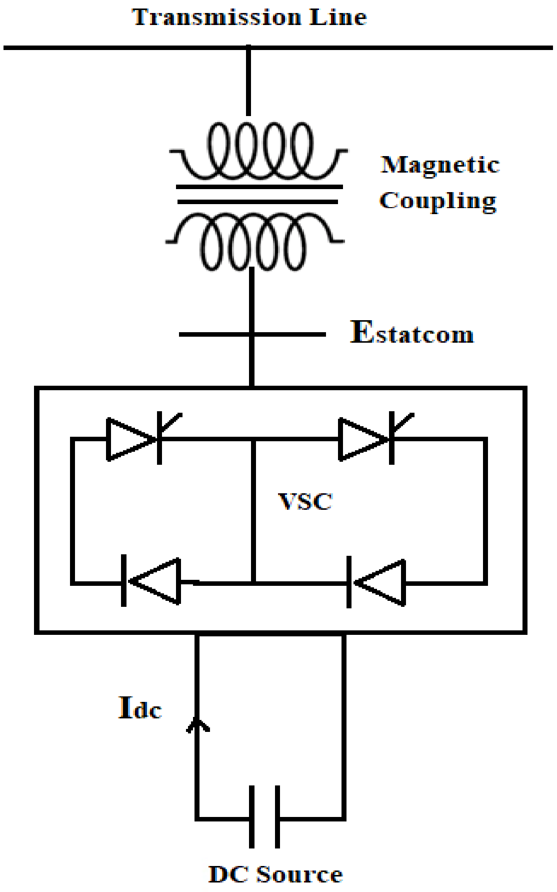

**Figure 1.17 STATCOM circuit**

$$V_j = \left[V_j^a, \theta_j^a \;\; V_j^b, \theta_j^b \;\; V_j^c, \theta_j^c\right]^t \tag{1.20}$$

$$E_{CR} = \left[V_{CR}^a, \delta_{CR}^a \;\; V_{CR}^b, \delta_{CR}^b \;\; V_{CR}^c, \delta_{CR}^c\right]^t \tag{1.21}$$

$$Y_{CR} = \begin{bmatrix} Y_{CRi}^{a} & 0 & 0 \\ 0 & Y_{CRi}^{b} & 0 \\ 0 & 0 & Y_{CRi}^{c} \end{bmatrix} \tag{1.22}$$

Thus, FACTS controls the characteristics of the power system to enhance its efficiency, flexibility, and reliability, depending upon current system requirements. In a congested system, FACTS controls and rectifies the cause of congestion to mitigate congestion

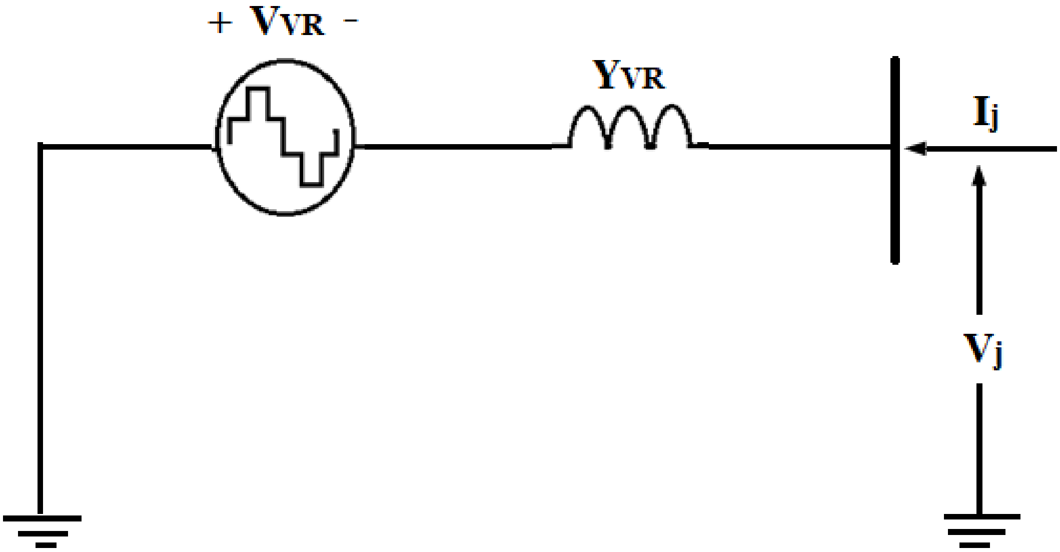

**Figure 1.18 Solid-state voltage source representation of STATCOM**

The type of FACTS device implemented depends upon the priority of the system whether a system has to work economically or efficiently and reliably [15].

### B) Tap Changing of Transformers

Transmission congestion management plays a crucial role to avoid line outages due to excessive power flow and to assure desired power flow through the line. Cost-free congestion management technique, through reactive power loss and line flow minimization, has been applied to the power system [16]. Line flows can be adjusted for relieving congestion without altering the actual real power flow in the line for minimizing fuel costs. For mitigating congestion, the control variables have been the tap settings in the transformer and the optimized size of TCSC. Nature-based simple intelligence techniques may be used for getting optimal values of control parameters.

Two winding transformers are considered here for analyzing the power flow models for load tap-changing (LTC) transformers. This model considers complex taps on both side windings of the transformer, while magnetizing branch represents the core losses of the transformer. LTC model without complex taps can be represented as:

$$\begin{bmatrix} I_i \\ I_j \end{bmatrix} = \frac{1}{T_i^2Y_i+U_j^2Y_j+Y_0}\begin{bmatrix} U_j^2Y_iY_j + Y_iY_0 & -T_iU_jY_iY_j \\ -T_iU_jY_iY_j & T_i^2Y_iY_j + Y_jY_0 \end{bmatrix}\begin{bmatrix} V_i \\ V_j \end{bmatrix} \quad (1.23)$$

In Equation (1.23) it is considered that the transformer is connected between bus i and j respectively. Here primary winding is connected to bus i whereas secondary is connected to bus j. Based on Equation (1.23), equations for power injection at buses may be derived. This method is very tedious, expressions may be derived by taking certain assumptions such as:

- Facility to change tap is available on the primary side only i.e., the value of $U_j$ will be equal to 1.
- Only primary side impedance is considered i.e., the admittance on the secondary side, $Y_j$ is equal to 0.
- The magnetizing impedance, $Y_0$ is negligible hence its effect on power flow solution is neglected.

Applying above mentioned assumptions Equation (1.23) can be rewritten as:

$$\begin{bmatrix} I_i \\ I_j \end{bmatrix} = \begin{bmatrix} Y_i & -T_iY_i \\ -T_iY_i & T_i^2Y_i \end{bmatrix}\begin{bmatrix} V_i \\ V_j \end{bmatrix} = \begin{bmatrix} Y_{ii} & -T_iY_{ij} \\ -T_iY_{ij} & T_i^2Y_{ij} \end{bmatrix}\begin{bmatrix} V_i \\ V_j \end{bmatrix} \quad (1.24)$$

For both ends of the transformer, the power flow equations can be now derived by applying design constrained values of $T_i$ as ($T_{i\,min} < T_i < T_{i\,max}$):

$$P_i = V_i^2G_{ii} + T_iV_iV_j\left[G_{ij}\cos\left(\theta_i - \theta_j\right) + B_{ij}\sin\left(\theta_i - \theta_j\right)\right] \quad (1.25)$$

$$Q_i = -V_i^2B_{ii} + T_iV_iV_j\left[G_{ij}\sin\left(\theta_i - \theta_j\right) - B_{ij}\cos\left(\theta_i - \theta_j\right)\right] (1.26)$$

$$P_j = T_i^2V_j^2G_{jj} + T_iV_iV_j\left[G_{ji}\cos\left(\theta_j - \theta_i\right) + B_{ij}\sin\left(\theta_j - \theta_i\right)\right] \quad (1.27)$$

$$Q_i = -T_i^2V_j^2B_{jj} + T_iV_iV_j\left[G_{ji}\sin\left(\theta_j - \theta_i\right) - B_{ji}\cos\left(\theta_j - \theta_i\right)\right] (1.28)$$

In the above equations,

$$\left.\begin{aligned} Y_{ii} = Y_{jj} = G_{ii} + jB_{ii} = Y_i \\ Y_{ij} = Y_{ji} = G_{ij} + jB_{ij} = -Y_i \end{aligned}\right\} \tag{1.29}$$

Using equations (1.25) to (1.28) and assuming that the LTC is regulating the magnitude of the nodal voltage at generating end, the equations for power flow (at bus i) can be written as:

$$\begin{bmatrix} \Delta P_i \\ \Delta P_j \\ \Delta Q_i \\ \Delta Q_j \end{bmatrix} = \begin{bmatrix} \frac{\partial P_i}{\partial \theta_i} & \frac{\partial P_i}{\partial \theta_j} & \frac{\partial P_i}{\partial T_i} T_i & \frac{\partial P_i}{\partial V_j} V_j \\ \frac{\partial P_j}{\partial \theta_i} & \frac{\partial P_j}{\partial \theta_j} & \frac{\partial P_j}{\partial T_i} T_i & \frac{\partial P_j}{\partial V_j} V_j \\ \frac{\partial Q_i}{\partial \theta_i} & \frac{\partial Q_i}{\partial \theta_j} & \frac{\partial Q_i}{\partial T_i} T_i & \frac{\partial Q_i}{\partial V_j} V_j \\ \frac{\partial Q_j}{\partial \theta_i} & \frac{\partial Q_j}{\partial \theta_j} & \frac{\partial Q_j}{\partial T_i} T_i & \frac{\partial P_i}{\partial V_j} V_j \end{bmatrix} \begin{bmatrix} \Delta \theta_i \\ \Delta \theta_j \\ \frac{\Delta T_i}{T_i} \\ \frac{\Delta V_m}{V_m} \end{bmatrix} \tag{1.30}$$

Now the Jacobian elements with specified tap variable $T_i$ and specified magnitude of the voltage at bus i, $V_i$ can be written as:

$$\frac{\partial P_i}{\partial \theta_i} = -\frac{\partial P_i}{\partial \theta_j} = -Q_i - V_i^2 B_{ii} \tag{1.31}$$

$$\frac{\partial P_i}{\partial T_i} T_i = -\frac{\partial P_i}{\partial V_j} V_j = P_i - V_i^2 G_{ii} \tag{1.32}$$

$$\frac{\partial Q_i}{\partial \theta_i} = -\frac{\partial Q_i}{\partial \theta_j} = P_i - V_i^2 G_{ii} \tag{1.33}$$

$$\frac{\partial Q_i}{\partial T_i} T_i = -\frac{\partial Q_i}{\partial V_j} V_j = Q_i + V_i^2 B_{ii} \tag{1.34}$$

$$\frac{\partial P_j}{\partial \theta_j} = -\frac{\partial P_j}{\partial \theta_i} = -Q_j - T_i^2 V_i^2 B_{jj} \tag{1.35}$$

$$\frac{\partial P_j}{\partial V_j} V_j = \frac{\partial P_i}{\partial T_i} T_i = P_j + T_i^2 V_j^2 G_{jj} \tag{1.36}$$

$$\frac{\partial Q_j}{\partial \theta_j} = -\frac{\partial Q_j}{\partial \theta_i} = P_j - T_i^2 V_j^2 G_{ii} \tag{1.37}$$

$$\frac{\partial Q_j}{\partial V_j} V_j = -\frac{\partial Q_j}{\partial T_i} T_i = Q_j - T_i^2 V_i^2 B_{jj} \tag{1.38}$$

After every iteration, the tap variable/ controller is updated as:

$$T_i^m = T_i^{(m-1)} + \left(\frac{\Delta T_i}{T_i}\right)^{(m)} T_i^{(m-1)} \tag{1.39}$$

Here 'm' represents the current iteration number.

The introduction of a voltage-controlled bus i.e., PVT bus with LTC model in power flow algorithm is beneficial as it behaves like a PV bus where control of voltage is carried out by LTC instead of a change of generator output.

Here the tap value $T_i$ is taken as a state variable while the node voltage, real power, and reactive power are pre-specified. The value of the tap variable, $T_i$ forms the basis of the type of bus:

- If $T_{imin} \leq T_i \leq T_{imax}$ then, the bus will act as PVT with a specified voltage
- If $T_i > T_{imax}$ than, $T_i$ is set at $T_{imax}$ and the bus behaves as a PQ bus.

#### 1.7.1.2 Non-Technical Methods to Mitigate Congestion

These are the methods considering operational costs. Under this category comes generator rescheduling (GR), Distributed generation (DG), curtailment of load, and nodal pricing-based methods.

#### A) Generator Rescheduling (GR)

In deregulated environment congestion is the major problem faced by an ISO which is creating a lot of technical and economic problems. Rescheduling of generators' active power outputs has been one of the most applied and apparent techniques of CM where only a few generators of the system take part in the rescheduling process. The generators selected to participate in the process of rescheduling are done with the help of generator sensitivity factors. In literature, it has been proposed that for generator rescheduling, firstly a method to determine the most suitable generators to participate in rescheduling has been introduced using the sensitivity of a particular generator to the power flowing in congested lines. Secondly, a technique based on an algorithm is applied to have minimum deviations of rescheduled active power values of the generator from the scheduled level [17].

The main purpose of the technique is to decrease the number of generators participating in the rescheduling process, as well as the active power rescheduled, which must be optimized to have minimum congestion cost together with alleviation of congestion in pool markets. In a congested power system, power flowing in different lines is not equally affected by the alteration in the real power yield of a particular generator. Thus, every generator is not to be rescheduled as rescheduling the power output has no significant effect on congested line flows. How sensitive a specific generator is to an overloaded line is used as the base to select the generator to participate in rescheduling to mitigate congestion. A suitable criterion is chosen so that participating generators may be the least in number with the lowest cost of congestion. The generator sensitivity factor can be defined as the ratio of change in real power flow $\Delta PG_{ij}$ in a line k, between buses i and j due to change in active power generation $\Delta PG_n$ for n$^{th}$ generator and the alteration in real power generation $\Delta PG_n$. Mathematically it can be represented as:

$$GSF = \frac{\Delta P_{ij}}{\Delta PG_n} \tag{1.40}$$

The generators with a maximum negative value of GSF are considered for participation in the rescheduling of active power to have a minimum cost of rescheduling.

### B) Distributed Generation (DG)

After the deregulation of the power system, the usage of DG has raised to a greater extent, which plays a crucial role in modern power systems operation and forecasting. In general, voltage profile improvement is the basic reason to employ DGs. In the literature authors proposed methods to obtain the most significant economic gains by employing new distributed generation technologies in the distribution system. Sometimes, owners of distributed generators are charged connection fees, even if significant amounts of money have been saved per year in delayed network improvements, reduced losses, unnecessary wholesale market purchases, and others. Giving the profit of DG to the owners enhances the repayment of their investments and encourages the employment of the distributed generator which has been very advantageous to the system [18]. An indices-based approach has been given to assess the technical advantages in a calculable manner. The authors worked on several indices such as:

1) voltage profile improvement index
2) line-loss reduction index
3) environmental impact reduction index and
4) DG benefit index [19]

For reducing voltage deviation, line losses, and enhance benefits of SO and consumers. Conventional and non-conventional energy resources can be used to power up DGs. [20],[21]. New DG technologies including IC engines, fuel cells, gas turbines, and microturbines utilizes conventional energy resources. However, non-conventional resource technologies such as biomass systems, Photo Voltaic, solar-thermal-electric systems, Wind Energy Conversion Systems, and geothermal systems have been seen as the most appropriate sources for DG. At present, DG may rate between a few kilowatts to 100 MW. Smaller DG units are installed in distribution networks and larger units are installed where sub-transmission lines intersect with gas pipelines. With the development of technology, some DG generates more effectively as compared to the traditional generation systems in terms of cost of generation and placement. DG has been potential application in those places where it is not possible to lay down a new power system framework. There has been some disadvantage of employing DG as its implementation has certain problems of voltage instability, low protection profiles, and reverse power flow [22].

### C) Curtailment of Load

Congestion can be alleviated by demand-side participation by load curtailment together with the rescheduling of real power generation. Rescheduling of generator with load curtailment is done by considering the sensitivity of the Generator to a particular congested line and the costs of generation and demand-side adjustments. OPF has been carried out for a re-dispatch of transactions. OPF formulation based on Particle Swarm Optimization (PSO) has been employed. to solve the power system problem. IEEE-30 bus System has been used to validate the proposed method and the results demonstrate that with the proposed technique cost of congestion management is effectually minimized with alleviation of congestion in the congested transmission lines. A model has been proposed for optimum curtailment of load to alleviate congestion in [23] for the bilateral pooled electricity market model. Congestion distribution factors have been applied to locate the FACTS devices for optimal load curtailment to mitigate congestion.

### D) Nodal Pricing Based Methods

Ward's minimum variance method provides high-resolution input data for a nodal model which sets the benchmark for efficiency and cluster analysis. Methods have been proposed for zonal configurations and tested for sensitivity to the number of zones and structural changes in the electricity market [24]. Furthermore, costs of electricity generation and transmission has been utilized for computing dispatch and re-dispatch costs of generation.

## 1.8 RESEARCH OBJECTIVES

### 1.8.1 To reduce active and reactive power losses by optimal placement of FACTS devices in a power system.

**Solution:** OPF has been performed with Newton Raphson's (NR) load flow analysis. The FACTS devices, SVC, and TCSC are located on IEEE 30-Bus system. FACTS are located with the help of Grey Wolf Optimization (GWO) and MATLAB/ SIMULINK. The results indicated that TCSC outperformed SVC when the power loss in the system is concerned. Here since the method applied is a cost-free method i.e. operational cost is kept constant, thus economics concerned with the capital and installation cost of FACTS is not considered.

### 1.8.2 To enhance Available Transfer Capacity and to minimize the losses using FACTS devices.

**Solution:** ATC being calculated by implementing Power Transfer Distribution Factors (PTDF). The FACTS device used here is TCSC. As TCSC is a series FACT device, it can regulate the line reactance directly to manipulate power flow through the line. The location of TCSC is obtained by the PTDF and its reactance is varied using GWO. The changed reactance values are applied to OPF through NR and new line flows are calculated. The location and sizing of TCSC which gives the maximum value of ATC and corresponding minimum values of power loss is the solution to the objective. The SIMULINK is operated two times. First time for ATC enhancement and the second time for power loss reduction. The OPF results for IEEE 30-Bus system are compared between GWO and Firefly Algorithm (FA). GWO outperformed FA.

### 1.8.3 To determine the optimal location and parameter setting of the FACTS device for congestion alleviation

**Solution:** This objective is achieved by creating congestion in the system by out-aging the line between two buses and system overloading by 150% and 180%. Then with the utilization of the sensitivity factor's optimal location of FACTS has been obtained and the parameter setting is done by applying the optimization methods. Here a new methodology to merge two well-known optimization techniques is also proposed. The results validate the methods as the objective is achieved.

### 1.8.4 To improve voltage profile and enhancement of system security under the congested condition of the power system using FACTS devices.

**Solution:** To manage congestion using the FACTS device, it is necessary to optimally locate it. Optimization of the control parameter, like reactance in the case of TCSC, plays a vital role in reducing congestion. The location of TCSC is optimized by a sensitivity factor called Line Utilization Factors (LUF) and Disparity Line Utilization Factors (DLUF). The line with the minimum value of DLUF is the location of TCSC. The reactance setting of TCSC is done with GWO so as to reduce voltage deviation and enhance the security margin of the system. This ultimately reduces congestion in the system to make it stable.

### 1.8.5 To manage congestion by using Rescheduling of the generators to reduce congestion costs.

**Solution:** This is one of the cost-free methods to mitigate congestion in the power system. Different generators of a system tend to affect the line flows of particular line/s. The individual effect of change in active power output of generator on congested lines is evaluated in contingency conditions with the help of the Generator

Sensitivity Factor (GSF). The generator with a maximum negative GSF value will participate in rescheduling. The extent of rescheduling is decided by GWO and the newly developed Hybrid PSO-GWO (HPSOGWO) so that congestion cost is minimum. PSO, GWO, and HPSOGWO are compared and HPSOGWO is found to be the best of the three.

## 1.9 ORGANIZATION OF THESIS

The thesis is organized into the following chapters:

**Chapter 1**, the current chapter, introduces the basic organization of the deregulated system and its effect on power system society. Starting from initial vertically aligned electrical utilities to the formation of horizontally aligned utilities has been detailed. The effects of deregulation on power system transmission have been illustrated. The congestion created due to overloading of transmission lines and the ill effects on voltage profile, power losses, transfer capacity of the line, and security margin are discussed. Different ways to mitigate congestion are conferred in detail.

**Chapter 2**, the literature on deregulation and congestion is reviewed. The work on different types of congestion mitigating methods which include both cost-free and non-cost-free methods has been detailed. Work done to mitigate congestion using FACTS devices has been reviewed. Also work done on the rescheduling of the generator, load curtailment, and application of DG to mitigate congestion has been studied and elaborated.

**Chapter 3** includes the minimization of line losses with the help of Grey Wolf Optimization (GWO). These losses are minimized after finding the optimal location of FACTS devices. TCSC and SVC are taken as series and shut-connected devices respectively to reduce the line losses. A comparative analysis is done to find the effectiveness of the FACTS devices on the line loss reduction.

**Chapter 4** covers the enhancement of ATC for congestion mitigation. The effect of congestion on line losses is elaborated. The available transfer capacity (ATC) of the line is reduced and power losses are increased with increased congestion in the line. TCSC is being used to regulate the reactance of the line. Constrained OPF is carried out with NR to get the line flows and to calculate the power loss in the line. TCSC has been located by using Power Transfer Distribution Factors (PTDF) at a position where the ATC value is maximum. The reactance parameter of TCSC is determined by the proposed optimization technique. Here other optimization techniques are compared with the proposed one for ATC maximization and power loss reduction.

**Chapter 5** describes the application of FACTS devices to mitigate congestion in the transmission line. The location of TCSC is determined with the help of sensitivity factors called Line Utilization Factors (LUF) & Disparity Line Utilization Factor (DLUF). The device is located at the line with a minimum value of DLUF. Constrained OPF with NR is carried out after TCSC is optimally located. Different optimization techniques are being compared here. This chapter also introduces a novel method to combine two optimization algorithms GWO and PSO to give Hybrid PSO-GWO. The results are evaluated with all three algorithms and are compared to prove the hybrid optimization technique is better than the parent algorithm.

**Chapter 6**, explains a non-technical method to alleviate congestion. Here re-scheduling of the real power of generators is explained for reducing congestion in the overloaded line. An outage of the line is created so that some of the lines get overloaded. Then the generator output is changed to see its effect on congested lines. The generator most suitable for rescheduling is obtained with the help of the Generator Sensitivity Factor (GSF). Generators with the most negative GSF are considered for rescheduling. The extent of rescheduling, to minimize congestion cost, is calculated and compared with the help of optimization techniques like GWO, PSO, and HPSOGWO. Chapter 6 includes detailed and conclusive remarks on methods of congestion mitigation applied, their advantages to the researchers, and prospects.

**Chapter 7** concludes the thesis with the conclusions obtained for individual objectives considered in each chapter.

# CHAPTER II

# LITERATURE REVIEW

For mitigating congestion, several techniques have been suggested in the literature. Congestion management can be done by considering the operational cost of the system. Based on the operational cost the technique may be cost-free (with no impact on operational cost) and non-cost-free (including operational cost). The cost-free methods are also called technical methods which include phase shifting or tap changing of transformers. Phase shifting of transformers has been implemented for a 24-hour schedule instead of current utilization only [25] and utilization of FACTS devices. Out of these two methods, the FACTS application is the most widely used method for managing congestion [28][29]. Other methods of congestion management are non-technical methods which impact operational costs. Generation Rescheduling (GR) [30], Distributed Generation (DG) [31], curtailment of load [32], and nodal pricing-based methods are categorized under non-technical methods.

## 2.1 TECHNICAL METHODS (Cost-free methods)

Those methods which do not affect the operational cost of the system are included in technical methods to mitigate congestion. Work done on congestion management by using tap changing transformer and implementing FACTS devices has been reviewed as follows:

### 2.1.1 Tap Changing Transformers

Renewable energy sources (RES) are very stochastic. Their integration with the main power grid increases the loop flows and the generation of variable energy congestion is created in the system. Phase-shifting transformers are best suited for diverting the power flows to mitigate congestion. The authors implemented 24-hour day-ahead scheduling of phase-shifting transformers to minimize the switching operations and reduce the operator involvement [25]. Further transmission congestion has been mitigated by minimizing the reactive power loss through targeted transmission lines in the power system. Here transformer tap settings and TCSC sizes are taken as the assessment variables for reactive power loss minimization. The mitigation of congestion is obtained by varying the control parameters in a coordinated manner [26]. Mitigating congestion only by using methods to apply tap changing transformers was not very efficient. Thus, a real power performance index-based approach has been adopted. The line flows are manipulated to relieve the congested lines hence here rated real power of the lines calculated by OPF is not changed. The manipulation of active power flows is obtained by adjustment of transformer tap positions in coordination with the insertion of TCSC in the lines. Here control variables used are transformer tap settings and optimal location and size of TCSC [27].

### 2.1.2 Implementation of FACTS Devices

FACTS device implementation is one of the most adopted methods to relieve the congested lines due to their capacity to assist the power systems to operate in a more supple, protected, financially viable, and secure regime. Faults and unwanted condition results in heavy line flows. Some part of the system gets heavily loaded while remaining woks under the lightly loaded condition that is way below their rated flow. This weakens system security and stability and also leads to high losses which in turn is very undesirable. Further, FACTS devices may be efficiently implemented into the system for enhancing the utilization of the existing system framework by overcoming the transmission constraints due to which some combinations of generation and demand are unviable.

A method for mitigating congestion has been proposed in [33], based on the sensitivity of line loss where the device is located, total active power loss, and real power flow performance index, to locate TCSC and thyristor-controlled phase angle regulators (TCPAR). An algorithm has been proposed in [34] for managing congestion by applying OPF. GA has been applied to get an optimal global solution for the objective function. Two very versatile FACTS devices named TCSC and UPFC are located on the congested lines considering the thermal limits as the constraint. Different numbers of two FACTS devices have been allocated in the IEEE 30-Bus system to mitigate congestion most efficiently. Further, LMP difference congestion rent contribution methodologies for allocating TCSC for mitigating congestion in IEEE 14, 30, 57 bus systems were proposed in [35].

Till now the objective functions considered were supporting each other. This made the process of managing congestion less efficient. As the objectives under consideration were solved leaving behind the other contradictive objectives. So, to counteract this problem a two-step method has been proposed in [36] to solve a multi-objective function with voltage profile improvement and enhancing security margin as two contradictive objectives. The first step included sequential quadratic programming to allocate TCSC and SVC for security margin enhancement and in the second step, a GA-based Fuzzy multi-objective algorithm has been applied to get the best-settled results for the objectives considered.

FACTS devices implementation is beneficial only if is located suitably. Hence certain metaheuristic methods like PSO have been proposed to locate TCSC [37] to reduce congestion of the system by minimizing the objective function which includes congestion cost and total generation cost. Results validated on IEEE 14 and 57 bus systems. The location of FACTS devices was decided with the help of several other heuristic methods but the efficiency of the FACTS was not fully achieved till the location of the device was done with the help of location indexes. In [38], the Real Power Performance Index (PPI) for optimal location of TCSC to mitigate congestion has been proposed. TCSC has been used for reducing transmission losses and generation costs to increase the readability and stability of the system. An optimized location out of three locations obtained by PPI is decided using the interior point method by minimizing production cost.

With the development of power electronics-based technologies, a new type of FACTS device was discovered and implemented in the power system. A high range of operations without sacrificing efficiency and security has been obtained with the implementation of newly developed FACTS. In this continuation a method where FACTS are clubbed with Power Oscillation Damper (POD) for series voltage compensation. Other newly developed FACTS devices such as SSSC, UPFC, and SSSC with POD have been tested in [39]. SSSC with POD gave better results as compared to

UPFC. Further third-generation FACTS devices such as STATCOM have been implemented in the system in [40]. The effect of this device on the reduction of congestion cost is studied while rescheduling the generators. Here three bid block structure is used with static security and voltage margin as constrained limits. Further, the effect of enhanced line loading on the power flow deviation has been studied in [41]. Here the power flows were redistributed together with rated voltages at different buses, which were deviated from rated values due to enhanced system loading by the application of SVC, TCSC, and UPFC. Here the results are validated on IEEE 14 bus system.

UPFC has been applied in the Indian 75 bus system and the new England 39 bus system [42] for mitigating congestion. The location of UPFC is determined by Power Transmission Congestion Distribution Factors (PTCDFUs). Works have been clubbed with generator rescheduling and newly developed FACTS device, IPFC together with UPFC and HVDC to reduce the cost of congestion in standard IEEE 30-Bus system in [43]. Firefly Algorithm (FA) has been applied to locate TCSC in the transmission line for increasing the transmission capacity of the line and reduce the congestion. The location of TCSC is obtained by using the system total reactive power loss factor and true power flow Performance Index (PI) in [44]. The results have been validated on IEEE 14 bus and IEEE 30-Bus test systems.

### 2.1.3 Congestion Mitigation by Optimal Location of FACTS Devices

More and more attention has been given to the most suitable location for FACTS devices. The devices are quite expensive hence once to be used in a power system so, they must be located at their exact position for maximum advantages. The location of FACTS controllers is based on the static or dynamic performance of the system. For improving the performance of FACTS devices Eigen Value Analysis and simulation in the time domain is to be performed for optimal parameter setting of the device as reported in [45]. The sensitivity factor method is one of the most efficient methods for the location of FACTS devices. Static modeling of FACTS is also performed with the help of these factors. Series FACTS device such as TCSC has been modeled as a series capacitor, simplifying the mathematical complications. Thus, a

FACTS device will give its most efficient output in alleviating congestion if located at the point of contingency or at a location near it. Numerous evolutionary algorithms have been recorded in the literature for locating the FACTS devices. In [46] an algorithm based on Particle Swarm Optimisation (PSO) has been proposed to alleviate congestion through proper locating and parameter optimization of UPFC. An algorithm that is a hybrid of the Bacterial Foraging (BF) and Nelder–Mead (NM) method has been proposed in [47] for solving OPF. The optimal location of the TCSC is determined by the penalty cost of emission while the parameter is optimized by the BF-NM algorithm. Firefly Algorithm (FA) has been proposed in [48] to mitigate congestion in the power system. The author has applied the Static Voltage Stability Index (SVSI) for obtaining a suitable location for TCSC and SVC. Thereafter Hybrid Cat Firefly Algorithm is applied to optimize the parameters of TCSC and SVC to reduce power loss in the system. A method to optimally locate TCSC has been discussed in [49] where power indexes have been utilized to locate TCSC for solving an objective to reduce system reactive power losses to reduce congestion in the system.

### 2.1.4 Application of Phase Shifting Transformers

With the enhancement of utilization of electrical energy due to the exponential development of industries, the need for additional power has been raised many folds. With less space, geographical location, and higher cost of incorporation it is economically non-feasible to start new power plants. Thus, the same power system framework has to be utilized for enhanced transmission and distribution creating congestion. One of the methods discussed in the literature to alleviate congestion is the use of phase-shifting transformers. The phase-shifting transformers help to redistribute the active power flows from the overloaded lines to the underloaded lines to alleviate the congestion. The main advantage of this method is that it avoids new production and re-dispatch which in general are costly methods.

A method has been proposed in [50], which describes the action of the phase-shifting transformers in the Benelux grid. 24 hours day-ahead scheduling is proposed for the operation of phase-shifting transformers. The author’s objective here is to reduce the number of operator interventions which in turn is achieved by switching the phase-shifting transformers as per the 24 hours schedule. The congestion in the system may also lead to unwanted voltage collapse and extreme blackouts. The loss of equipment and its replacement is very costly. A method to divert the real power flow through the congested lines to the underloaded lines by the application of PST has been proposed in [51]. To realize this diversion a variable phase angle shift with the help of on-load tap changers is deployed. This results in a change in the resultant phase angle. The author suggested a method to control PST to obtain the best or nearly ideal situation for a given system in [52]. PSO-based method for optimizing PST settings is presented. The optimization objective here is to minimize the unscheduled active power flow through a given IEEE 118 bus system.

## 2.2 NON-TECHNICAL METHODS (NON-COST-FREE METHODS)

### 2.2.1 Generator Rescheduling

A comparison of the cost-free and non-cost-free methods to mitigate congestion has been reported in [53]. Generator rescheduling and load curtailment are compared with the application of FACTS devices for congestion management. When non-cost-free methods, such as generator rescheduling are applied, the congestion problem is managed by taking into account the economy as the main objective, instead of the technical aspects. So, the generator rescheduling is considered a non-technical method of congestion mitigation. Load curtailment is one of the methods to mitigate congestion resulting in an increment in the cost of generation. This is an expensive method, so work has been done in [54] where a sensitivity-based rescheduling of generation and/or load curtailment has been suggested for congestion management. The sensitivity index is the ratio of change in line current and change in bus injections. As load curtailment directly increases the congestion cost, here generator rescheduling is done to mitigate congestion together with load curtailment. In some cases, only generator rescheduling can solve the objective of congestion mitigation. In this step, work has been proposed in [55] where Ant Lion Optimization (ALO) algorithm-based generator real power rescheduling for mitigating congestion has been done. The selection is based on the sensitivity factors called Generator Sensitivity Factors (GSF). GSF relates alteration in the real power flow in a line due to a change in the scheduled active power output of a generator. This method was found useful when the congestion is due to an outage of a line or a sudden change in the load.

An improved method to reduce the cost of rescheduling has been suggested in [56] where the author has proposed an algorithm to mitigate the congestion in modified IEEE 30 and IEEE 57 bus systems by implementing PSO. The method has been implemented to relieve overloaded lines with the minimal rescheduling of generator active power. Line loading and bus voltages have been the constraints that are considered while rescheduling the generators. Generator rescheduling in the deregulated environment is in the pocket of private /public sector generators in the deregulated scenario. Thus, to increase healthy competition some financial benefits are to be provided to generators to motivate them for participating in the rescheduling process. For achieving this a method has been suggested in [57]. In this paper author presented a solution, keeping benefit maximization, for congestion management in a multi-transaction-based distributed power market. The algorithm presented deals with a multi-efficacy arrangement to get coordination among different market players for achieving the benefits of investment.

Further works have been reported to enhance the efficiency of the process of rescheduling [58]. The work has been focused on generator rescheduling for mitigating transmission congestion. After calculating the GSF, generators have been selected for rescheduling. The generators having large and non-uniform values of GSF have been chosen for rescheduling. FA has been utilized for getting the values of change in active power generation. Similarly, in [59] a PSO-ITVAC-based method is proposed to calculate the cost of rescheduling the active powers of the generator. The proposed algorithm is tested on the IEEE 30-bus system and IEEE 118-bus system for reducing/ minimizing the congestion cost for rescheduling generators. Some authors proposed more efficient algorithms like Black Hole Algorithm (BHA) to optimize the modification of power generation based on GSF during congested conditions [60]. Here author proposed generator rescheduling for mitigating congestion using GSF for selecting the participating generator. The sensitivity of all generators for the change in the power flow in congested lines has been calculated. The generator participating in rescheduling, reschedule their power so that the congestion cost is minimum.

Literature discloses that several methods/ techniques have been proposed and executed by research scholars in the past to resolve the CM problem. After all of the methods, the main necessity that came into existence was the effectiveness by which an algorithm can reschedule a generator's output so that as per the bids provided by the generator a minimum rescheduled generation cost may occur.

The problem with the traditional optimization techniques is that these do not function with the efficacy as required for the systems with increased nonlinearity and dimensions. Nature-based metaheuristic algorithms have shown very promising results while handling such complexities. Based on this line of operation, FFA has been proposed in [61]. Here generator active power rescheduling through Firefly Algorithm (FFA) for reducing transmission network congestion in deregulated power systems has been discussed. The selection of generators has been done without the sensitivity factors only through FFA.

The author has proposed Teaching Learning-based algorithm (TLBO) in [62] intending to effectively relieve congestion in the transmission line with minimum deviation in initial generation and, hence, congestion cost. The application of PSO has been proposed in [63] for generator rescheduling. The author formulated the generator rescheduling problem as OPF and implemented PSO to give a good degree of accuracy to calculate the rescheduled value of power at the lowest congestion cost. The results have been validated on the IEEE 30-Bus system. Another meta-heuristic Satin Bowerbird Optimization (SBO) algorithm for congestion management (CM) in the deregulated power system has been proposed in [64].

An advanced Twin Extremity Chaotic Map Adaptive Particle Swarm Optimization (TECM-PSO) algorithm has been proposed in [65] to manage the nonlinear CM cost problem. The proposed approach is applied in two steps. In the first step by applying the robust upstream real capacity tracing method, an exact number of generators participating in the process of rescheduling is calculated. This approach requires the least information about generator units. The second step applies the TECM-PSO algorithm for minimum possible congestion cost while reducing the overloads on all the lines.

### 2.2.2 Distributed Generation

Deregulation in power systems has brought enhanced attention to distributed generation (DG). The DG incorporation is playing an important role in electric power systems planning. There are numerous benefits of DG obtained by incorporating it with the power system. It has shown numerous economic benefits over other technologies incorporated in the deregulated power system network. But DG incorporated into the system is beneficial only when it is optimally located and scheduled for its operation and capacity. In [66] an algorithm is presented to find the bus location which is most sensitive to voltage collapse. The algorithm is based on the continuous power flow method. Once the location of the bus is determined, DG units are applied. The capacity of the units is determined by a multi-objective function which has been solved with the help of the Placement Algorithm. The results are validated on the standard 34 bus system.

The author applied a simple orthodox N-R method to solve non-linear power system equations of form $F(x) = 0$, in polar form with the changed bus data to implement the effect of DG in [67]. The bus where DG is connected has been considered a PV bus such that the reactive power of DG equals 20% of the active power generated. Thus, optimal allocation is the best way to take advantage of DG in overcoming the overloading of lines and hence alleviate congestion. A two-stage technology has been proposed for optimally allocating DG in [68]. The aim has been to reduce system costs for enhanced total system benefits (TSB). There has been an optimal size and location of DG for its implementation cost and investment payback time. A new hybrid GA/PSO for optimally locating DG on the distribution system with an objective to minimize power losses, stabilize voltage profiles and better voltage regulation has been presented in [69].

In [70] a novel multi-objective method for optimizing DG placement, size, and pricing at the same time has been discussed. The proposed method has been applied keeping given the economic objectives of the DG and the Discos. The author proposed a multi-objective particle swarm optimization (MOPSO).

So, from the literature survey, it can be concluded that if the rating and location of DG are inappropriate its penetration level will cause unwanted complications in the power system. The major problems created due to inappropriate placement of DG are increased power losses, unsynchronised system frequencies, and significant voltage deviations. Thus, suitably rated DG must be optimally located for system voltage stability and grid security. The DGs participate in the deregulated system to earn revenues in decent amounts to gain profits above operational costs. So economic objectives are to be taken under consideration while DG is to be placed in the system. Not only suitable location affects the economy of the system but also proper rating and output of DG play a crucial role in a secured power system with the least congestion. This objective has been considered in [71] where a multi-objective optimization algorithm based on the supervised Big Bang–Big Crunch method for optimal planning of dispatchable distributed generators has been worked out. The proposed method objective is to increase the system PI by optimizing the size and location of DG connected to distribution networks. Comparison between different metaheuristic algorithms has been done in [72] where the author investigated the relation of incorporating DG to the power system reliability. The virus colony search (VCS) algorithm is implemented to optimize the location and size of DG's for the betterment of the reliability indices. The results have been validated on IEEE 34 bus system. Results from VCS have been compared to those obtained by GA, PSO, DE, MOPSO, MSFLA, GSA, BBO, HBB-BC, and GSO algorithms.

### 2.2.3 Curtailment of Load

With the abrupt increment in system loading, sudden unpredicted outage of any line, or failure of any power system security element including generator, the power system may enter a zone of emergency state with very low system reliability and stability. These problems may cause overloading of some of the very crucial lines, change of system frequency, and voltage collapse with angular instability. Thus, the system becomes congested which may lead to system failure if not prevented early.

Higher nodal prices are also the outcome of a congested system. Thus, congestion has to be mitigated at any cost by either rescheduling generators or load curtailment or both have to be done simultaneously. Load shedding can be explained as the method which results in a decrease of load demand of the power system at a particular instant of time to achieve the equilibrium state of the system. Load shedding is a very important part of deregulated power system where there is a shortage of spinning reserve or small tie-line power capacity to make the system stable.

The ISO plays a major role here to select the most suitable method to alleviate congested lines. For an IEEE 30-Bus system as a test system, multicriteria performance indices have been proposed in [73] so that customers, traders, and system operators are in a position to select the most suitable and effective way to alleviate congestion. Load curtailment as a small part of transactions in the physical transmission system can be a way to relieve congestion. The approach has been tested on a modified IEEE 30-Bus system. A method named Central Limit Theorem has been proposed in [74] to find the probability of load curtailment by approximating the capacity of energy storage devices. The author here mathematically explained the power system network as an infrastructure constituting electricity demand, capability to generate, and behavior of loads. In [75] an OPF-based evolutionary programming (EP) technique has been proposed for mitigating transmission congestion in deregulated power systems using load curtailment together with generation rescheduling. The results obtained have been compared with the Improved Quadratic Interior Point (IQIP) method based on OPF and validated on the European UCTE 2383- bus system.

A new CM approach has been proposed by taking a multi-objective function which includes several contradictory objectives such as rescheduling of generation and load shedding costs, social welfare, and minimization of load shedding in [76], Load served maximization and load served error minimization. Here the objective has been applied to the voltage-dependent load model instead of previously used constant load models. When security constraints are considered, solving a multi-objective CM problem is very tedious and difficult to be solved. The traditional techniques stick to local minima. Thus, requires an unorthodox method that can take care of the complex non-linear combined multi-objective power system equations. These methods must be able to search for a global minima/ maximum. Further, the method must be able to optimize the conflicting objectives if are considered together. To overcome this difficulty Fuzzy models have been incorporated in [77] with EP algorithms. Here the author has suggested an efficient method for mitigating congestion This paper presents an efficient method applied to a pool-based market system with two conflicting objectives. Minimization of congestion cost and line overload reduction are two objectives where load shedding is done if generation rescheduling only is not able to relieve congestion.

### 2.2.4 Congestion Mitigation Using Multi-Objective Functions

In a deregulated power system, the stability and security of the system depend on several constraints. These constraints when considered together for mitigating congestion give more promising results as compared to an individual. In literature, work has been suggested by applying multi-objective functions for transmission congestion management. Conflicting objectives which include the social welfare maximization and the emission impacts minimization has been applied in [78] for CM. A multi-objective optimization algorithm named Modified Non-dominated Sorting Genetic Algorithm II (MNSGA-II) is applied here for achieving the objectives considered. The centralized and decentralized CM is achieved by solving for multi-objective functions. New strategies are proposed in [79] which incorporate the currently used Multi-objective Differential Evolution algorithm. Here the OPF-based multi-objective CM problem is solved by applying the proposed technique to reduce congestion cost and fuel cost as the objectives. The method here is tested on the standard IEEE-30 bus test system.

In [80], a multi-objective function considering reduction of operational cost, reduction in emission, and enhancement in loading of transmission lines being solved by DRPs and rescheduling of generators. The multi-objective particle swarm optimization (MOPSO) algorithm has been proposed for the said purpose. The author proposed a CM problem by applying two objective functions in [81]. The first objective function is to minimize the total cost of generation without considering bidding prices and with bidding prizes the objective is to reduce congestion cost. The second objective considered is the reduction of total transmission losses. Multi-objective glow-worm swarm optimization (MO-GSO) algorithm is proposed here to solve the CM objectives.

## 2.3 SHORTCOMINGS OF EXISTING WORK

The literature is being studied extensively for methods to mitigate power system congestion and related issues, in the deregulated environment. It is found that there has been a certain lacking in the methods and devices selected. The author has found some of the shortcomings listed below:

a) In many congestions mitigating methodologies, a linearized DC power system model is implemented. The said model though simplifies the system for problem formulation and calculations, but it is based on several assumptions. The assumptions make the model unsuitable for extensive and more accurate calculations.

b) Costlier FACTS devices are being utilized instead of less costly devices for achieving high efficiency.

c) Only technical benefits of optimization methods have been considered. Social welfare maximization and line overloading problems are solved separately in most cases.

d) In literature, at many places, while locating FACTS devices no sensitivity factor is used. Instead, certain optimization algorithms are implemented for location.

## 2.4 AUTHOR’S CONTRIBUTION

The above-mentioned shortcomings in the implementation of congestion management techniques in deregulated power systems have been reviewed by the author and made his contribution which is summarised below:

a) The AC load flow model of the power system has been implemented to take care of all the constraints which were not considered previously by many authors. This made the research more realistic with practical solutions to the objective functions considered.

b) The author used TCSC as a FACTS device. TCSC is a very versatile device, is implemented in the system under consideration, and results obtained satisfy the motive of the objective function. TCSC costs much less than other devices like UPFC and STATCOM. Thus, is quite economic to be allocated in the power system for reactance manipulation.

c) The author applied the optimization techniques for solving a multi-objective function, which includes both the social welfare and technical efficiency of the device. The optimization techniques implemented here have been proved to be efficient and economic, moreover are solved simultaneously.

d) Sensitivity factors are used in this research for the location of FACTS devices as well as for deciding the generator to be rescheduled.

e) The author has applied a novel method to merge two well-known algorithms i.e., Grey Wolf Optimization (GWO) and Particle Swarm Optimization (PSO) for FACTS allocation as well as to optimize the rescheduled active power output of generators participating in rescheduling to mitigate congestion.

# CHAPTER III

# POWER LOSS MINIMIZATION BY OPTIMALLY LOCATING FACTS DEVICES

## 3.1 INTRODUCTION

The Electrical Power System (EPS) is one of the oldest and most traditional branches of electrical engineering. Growth in population and increased need for power in developing industries resulted in more advanced technologies to produce and transmit power to loads. With the increased transmission the active and reactive power losses also increased, which results in transmission congestion. The application of optimization methods is one of the technical improvement tools to reduce these losses. The methods are efficient enough to assure better electrical and economic performance of the (EPS). To analyze the optimization problem, there are many controllable parameters of EPS. Planning for future high-power demands involves a huge fortune to be invested with many complex constraints that have to be foreseen. A system for planning the power system expansion has been proposed so that the outage of heavily loaded may not affect the other interconnected lines [82]. The concept of optimization algorithms for EPS planning, energy transmission, and giving mathematical relations for power system inputs and outputs have been started in the mid-’60s. The formalized decision-making was done considering several technical and non-technical constraints while formulating objective functions [83]. This resulted in a sudden increase in research activities relating to the problems encountered in power systems with the advancement in the development of evolutionary optimization methods. The problems faced in the power system when performing OPF, which is an extension of economic load dispatch included under load optimum setting of transformer taps, control of active and reactive power generations, minimizing active and reactive power loss (both in transmission and distribution), and optimal control of other energy control devices. The research has been extended in the field of optimal reactive planning, transmission expansion, and increment of available transfer capabilities in interconnected networks. With time the effectiveness of optimization techniques increased which supported the research in the field of improving the power system quality, reliability, and efficiency. The control actions in EPS are generally achieved by optimal coordination between different controlling devices. The end goal of these devices can be summarised as below:

1) Protection of equipment connected in the EPS for power system integrity.
2) Supplying quality power to the loads
3) Reliable and safe operation of the system
4) Operation of the system efficiently and economically
5) Control of system in an emergency state
6) System restoration to a stable state after being subjected to transients in the shortest time.

With the increase in technology, new optimization methods have been developed which provides new tools for solving a complicated power system problem. The power system is quite complex when mathematically modeled. The modeling equations are highly non-linear due to the presence of a huge number of constraints and devices in the system. These equations cannot be solved by direct methods proposed in the literature. The most effective way to solve these interconnected complex mathematical problems is through newly developed iterative optimization techniques. These optimization techniques not only decrease the complexity of equations but also linearize the equations by considering small deviations during the operating conditions.

A number of optimization techniques have been proposed in the literature [84]-[91]. The most popular and effective methods are GA, Fuzzy embedded GA, Dedicated modified GA, Fuzzy Logic, PSO, DPSO, Linear Quadratic programming, etc. These optimization techniques are nature-based search algorithms that mimic specific natural techniques with which unique to species. The application of these methods gave promising results in obtaining the optimal solution to the power system problems. But a different method is suitable for a different set of equations due to the special characteristics of the algorithm applied.

## 3.2 GENERAL ASPECTS OF CONTROL IN A POWER SYSTEM

### 3.2.1 Flexible AC Transmission Systems

With technological advancements in power electronics, FACTS devices have been implemented in a huge segment of the power system. These devices elevate the performance characteristics of power system components to increase the efficiency and reliability of the system [92],[93]. Utilization of the installed capacity of the existing power system has been increased manifolds by the implementation of FACTS devices in transmission and distribution networks. The use of FACTS devices allows the control corresponding to the flow of power through certain lines, to increase the power transmission capacity under normal and system contingency conditions. FACTS plays a very crucial role in increasing the power transfer capacity of a specific transmission line so that it may operate at its full capacity near to its thermal limits without getting damaged and at the same time the system can maintain stability. At the time of system failure, FACTS helps to regain stability and control over real-time power flowing through the system. The goal of FACTS devices to increase power transmission capacity implies that a given transmission line may be able to operate near its thermal limits, allowing a greater amount of current to flow through its serial impedance. At the same time, it must maintain the stability of the system by employing appropriate real-time control of the power flow during and after a system failure [93].

When a number of these devices are connected in the system, the controlled coordination between these devices helps to avoid undesirable interactions between different interconnected areas, hence increasing system reliability. FACTS have been developed for optimizing strategies, adequate communication systems, and important security protocols.

Different types of FACTS devices are explained in Chapter-1.

### 3.2.2 Reactive Power Compensation

Maintaining voltage profiles and controlling reactive power are the areas of concern for maintaining stability in EPS. To maintain the quality of power in the system, V-Q characteristics must be under control. Reactive power control permits a way to stabilize the voltage profile, effective and efficient utilization of power transfer capabilities, and enhance of stability range of the system [94], [95]. The voltage profile control makes the objective function much more complex as the function becomes multivariant. So, frequency control is much simpler as for a single unique frequency area there can be several different voltage nodes. For balancing the reactive power in the system there must be proper voltage control. Reactive power compensation depends on its socio-economic impact on the end-user.

### 3.2.3 Basic Concepts of Reactive Power Flow

Balancing reactive power is the basic feature of the compensation and regulation of reactive power. The reactive power generated by the shunt capacitance of the transmission line depends on voltage and is proportionate to the square of the voltage. For maintaining the rated voltage within limits, the reactive power consumption is kept constant. On the other hand, the serial inductance of the power lines utilizes reactive power proportionate to the square of the current. The value of current changes with the change in load from the high value at full load condition to low at off-peak hours so the reactive power utilization is altered with the load. This results in a change of reactive flux. Figure 3.1 shows the π model for the transmission line, where B is the susceptance.

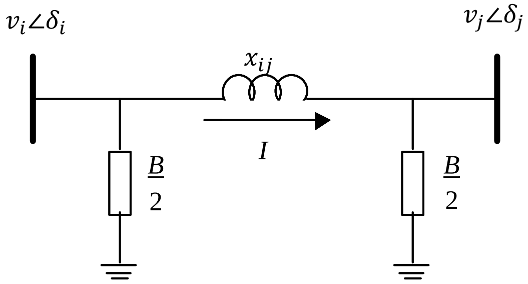

**Figure 3.1 π model of a transmission line**

Production of the Shunt reactive power in the transmission line = $v^2B$ (relatively constant)

Power consumption of the transmission line = $I^2x_{ij}$ (variable)

As the ratio $x/r$ increases (high-voltage transmission systems where $r$ is the resistance of the transmission line and $x$ its reactance) and the power factor is modified, the effect of the reactive current is greater on the voltage change. This can be observed from equation (3.1) when analyzing the phasor diagram of Figure 3.2 [89],

where $\mathit{\Delta} v = v_i - v_j$.

$$\mathit{\Delta} v = \frac{P}{v_j} r + \frac{Q}{v_j} x \tag{3.1}$$

For small angular differences, the reactive power tends to circulate from the highest voltage node to the lowest voltage node, this is determined by the reactive power flux equation (3.2), for the transmission line shown in Figure 3.3.

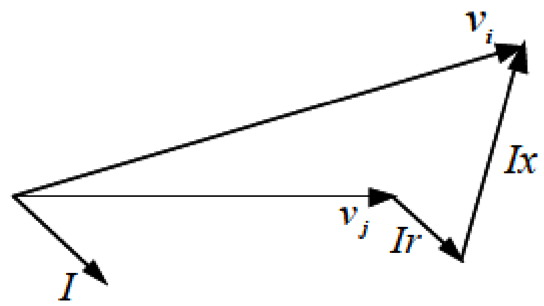

**Figure 3.2 Phasor diagram with delayed power factor**

For small angular differences, the reactive power tends to circulate from the highest voltage node to the lowest voltage node, this is determined by the reactive power flux equation (2), for the transmission line shown in Figure 3.3.

$$Q_{ij} = \frac{v_i}{x_{ij}} (v_i - v_j \cos \delta) \tag{3.2}$$

here, $\delta = \delta_i - \delta_j$

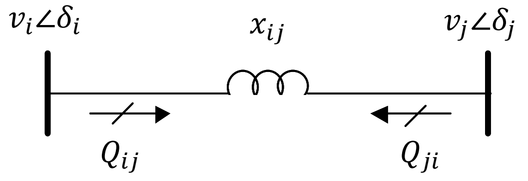

**Figure 3.3 Reactive power flow in a transmission line**

The losses in the transmission line can be calculated by means of the following expression:

$$Q_p = Q_{ij} + Q_{ji} \tag{3.3}$$

Substituting the equations of $Q_{ij}$ and $Q_{ji}$

$$Q_p = \frac{v_i^2}{x_{ij}} + \frac{v_j^2}{x_{ij}} - \frac{2v_i v_j}{x_{ij}} \cos \delta \tag{3.4}$$

The reactive power depends on the square of the voltage difference as can be seen from equation (3.4). The voltage drop produced by reactive power flow depends inversely on the reactance. The higher the voltage difference greater will be the reactive power consumption by the transmission line elements. So reactive power loss shows highly non-linear behaviour. The magnitude of reactive power flow at the end of the line depends upon the consumption of reactive power and charging currents. To maintain a constant voltage, the reactive power compensators supply reactive power as per the varying demand. Thus, there is a reactive power exchange between generators, resulting in an altered voltage profile that depends on reducing the reactive flow in the paths of higher impedance. So, it can be seen that to avoid the deterioration of the voltage profile the long-distance reactive power flow is to be reduced or eliminated. To control the voltage profile, injection of high values of current results in higher transmission losses, which in turn increases the complications and higher cost of operation. To maintain a voltage profile there is a tendency to supply reactive power through the least impedance lines.

Equation (3.5) shows that the ratio of reactive flows depends on the reactance of the branches, Figure 3.4 [80].

$$\frac{Q_{ij}}{Q_{kj}} = \frac{x_{kj}}{x_{ij}} \tag{3.5}$$

Where it is considered that the voltages $v_i$

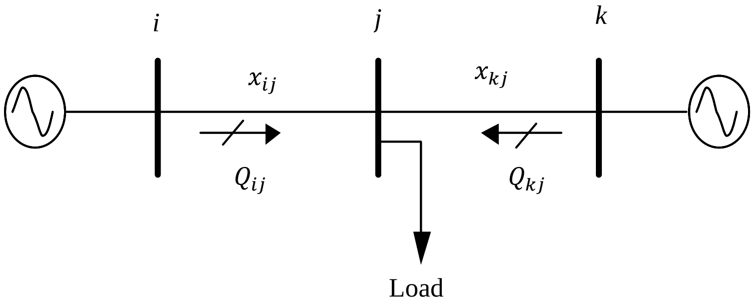

**Figure 3.4 Electrical power system (EPS) of 2 machines**

The need for controllable sources of reactive power can be summarized fundamentally in three essential points.

1. Check the voltage at nominal values: When sudden changes in load or topology occur, it may be necessary to correct the voltage in a few cycles. For other voltage variations, the correction can be made in seconds. Failure to correct voltage deviations, even if temporary, can result in damage to the user equipment.
2. Adjust the voltage profile on the network: To avoid the circulation of reactive power and thereby reduce energy losses by making better use of the transmission and transformation equipment capacity.
3. Maintain the timing of the generators: Voltage control through controllable sources of reactive power has stabilizing effects on the EPS, in the presence of disturbances that cause the rotors to change their relative positions. Reactive sources can enhance both small-signal stability and transient stability.

The voltage profile control at transmission levels is achieved by different operating techniques. Passive compensation equipment in shunt, like mechanically operated reactors and capacitors; changing transformer leads, and opening and closing transmission lines. The voltage profile can also be maintained by series capacitive compensation. However, for continuous monitoring and maintenance, equipment like Automatic Voltage Regulators (AVR), Synchronous Condensers (SC), FACTS such as SVC and TCSC, are installed at particular locations in the transmission network [92],[93].

Any FACTS device is connected in EPS depending upon its type, size/parameters, and location. EPS is subjected to several contingencies like outages of line or fault due to overloading or short-circuiting. Thus, before locating any FACTS device, the power system is analyzed which includes: fault studies, power flow studies, transient stability studies, small-signal stability studies, and harmonic studies. In a long transmission line, voltage control requires specific control methods and devices. The research involves detection of whether series or shunt or a combination of two has to be improvised [97].

The dynamic and transient stability of the system affects the reliability of chosen compensation technique. Other constraints related to the application of FACTS devices include harmonics linked with Power electronics-based devices and the menacing subsynchronous resonance associated with series capacitors. Thus, all such factors are to be considered and taken into account in planning and operational studies before the implementation of FACTS in a particular power system.

Sensitivity coefficients have emerged as a promising way to implement a voltage control FACTS device at the most suitable location. Depending on the desired outcome of the formulated objective function, large or small quantitative values of these coefficients provide useful information about the location where the device should be connected. These sensitivity coefficients must be evaluated extensively for diverse operating situations so that the most suitable index is available to suit a particular condition to be encountered. [98].

The sensitivity coefficients are most efficiently applied to:

- Estimate variation in bus voltage when a capacitor/reactor is connected to the system.
- Determine the variations in generated reactive power when a highly reactive load is connected/disconnected.
- Locate the lines where there is a maximum influence in power flow with a change in output of a particular generator.
- Determine the effective tap change for a load bus voltage control and also detect the reactive power loss due to tap changing.
- Evaluate the variation in system reactive power when reactive power is injected at a junction in EPS.

## 3.3 STATIC VAR COMPENSATOR (SVC) WORKING

Static VAR compensators are usually comprised of passive elements like capacitor banks and/or reactors. With the advancements in power electronics technology, very fast and accurate control strategies have been developed which can even respond in one cycle to connect an SVC to the system for control action. The connection and interruption of the capacitors are done by discreetly controlling the switching of thyristors. The switching periods are continuously changed as per the requirement by varying the firing angle of the thyristors. The result is obtained in the form of continuous control of reactive current. Closed-loop control strategies are implemented on SVCs for proper control of voltage and reactive power characteristics in transmission systems [99]. The control strategy of SVC comprises a primary voltage control loop and a secondary superimposed reactive power control loop, which are very useful in the determination of steady-state characteristics of a power system. Also, the stability characteristics of the applied control loop and its dependency on the current state of operation of the power system can be most suitably analyzed with the help of the closed-loop transfer function of the system. The control schematic of SVC is shown in Figure 3.5. which represents proportional control strategy where the error signal is transferred to the susceptance compensator.

a) $I_{SVC}$ presents the current flowing from SVC to the power system.
b) $B_{SVC}$ is the SVC equivalent susceptance
c) $v_t$ is the voltage at the EPS terminals
d) $V_v$ is the signal proportional to $v_t$ at the output of the measuring device.
e) $G_m(s)$ is the transfer function of the measuring device,
f) $G_r(s)$ is the transfer function of the voltage controller, and
g) $G_y(s)$ is the transfer function of the trigger control scheme in thyristors

The relation between current from SVC and the terminal voltage of the power system can be given by equation (3.6)

$$I_{SVC} = B_{SVC} v_t \tag{3.6}$$

Steady-state control characteristics can be plotted from equation (3.6) for the static compensator.

This characteristic is very important as it determines the operation of SVC in a linear zone of control. The curve obtained from equation (3.6) is plotted as a function of the reference voltage, $v_{ref}$ and the slope of the operating curve.

The operating characteristic curve plotted is shown in Figure 3.6. Here $k_a$ is the controller gain. The voltage in the system is controlled as per the characteristic slope

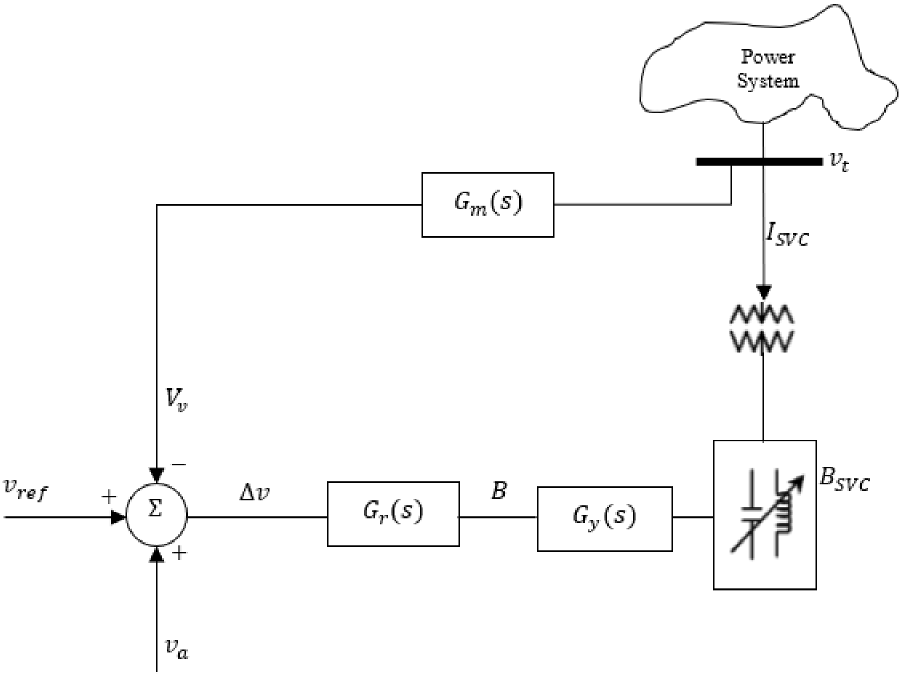

**Figure 3.5 Control scheme of an SVC using voltage feedback**

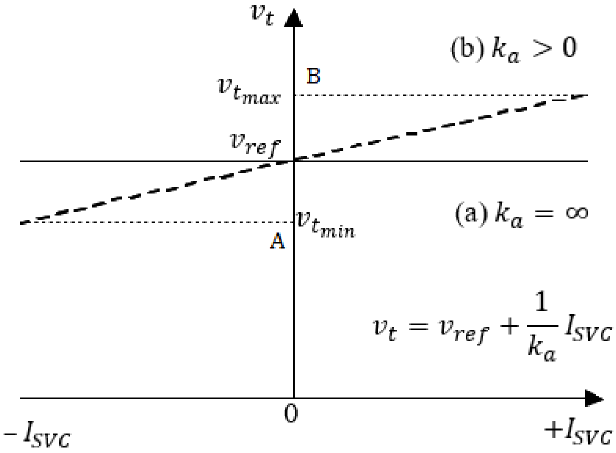

**Figure 3.6 Operating characteristics of an SVC**

.

The voltage can be controlled in two ways as per the slope selected:

a) Flat control of voltage: Here for all operating conditions a constant voltage is applied at the compensator terminal with infinite voltage regulator gain.

b) Polarized control of voltage: For all operating conditions, voltage regulator gain is adjusted to a finite positive value and the magnitude of the voltage applied at the compensator is kept approximately equal to the reference value.

To get high voltage gain out of the controller and to increase the compensator response rate small slopes of the characteristic curve are considered. This can also be achieved by reducing the controller's time constant. The SVC response is also affected by the short circuit tendencies of a power system. The operating characteristics of the power system are modeled with the help of its Thevenin's Equivalent as seen from the node which is compensated. At this point/node, the system impedance is considered equal to the short circuit reactance [100] for voltage regulation studies.

The compensator response is quick for the power system with low capacity to withstand contingency conditions as for the system with low short circuit capacity the compensator reaction time will be very small. On the other hand, in a system with an increased level of short circuit capacity, the response time of the compensator is quite high. Dynamic stability and steady-state studies of the power system are the core criteria to determine the value of the slope. This evidences that proper selection of voltage regulator time constant is essential to set the response time of regulator for stability requirement [101]. There are three zones in the operating characteristics from Figure 3.6.

1. The zone between A and B is the linear zone of operation where SVC terminal voltage is varied from minimum operating voltage, $v_{t_{min}}$ to maximum voltage $v_{t_{max}}$.
2. There is a low voltage operating area where the compensator is operating with its lowest control limit. So, the voltage regulating capacity is lost. This zone indicates that the operation of SVC is controlled by the rating of its capacitive branch. Here the terminal voltage of SVC ranges between 0 and $v_{t_{min}}$, following the power system requirements.
3. The third zone of operation is the area in which SVC operates from 0 to $v_{t_{max}}$. This area is called an overvoltage operating area. In this operating area, SVC mainly exhibits the voltage variation characteristics corresponding to the inductive branch of SVC.

Mathematically, with slope $m$, in normal operating mode, the voltage regulating characteristic of the compensator can be given by:

$$v_t = v_{ref} + mI_{SVC} \tag{3.7}$$

Here, $I_{SVC}$ must satisfy the constraints:

$$I_{S_{min}} < I_{SVC} < I_{S_{max}} \tag{3.8}$$

Where, $I_{S_{min}}$ and $I_{S_{max}}$ represent the minimum and maximum values of current injection in the capacitive and inductive branches of the compensator respectively.

The low voltage operation of the SVC corresponds to a fixed capacitor, explained by the relation:

$$I_{SVC} = B_{S_{min}} v_t \tag{3.9}$$

Where $B_{S_{min}}$ represents the capacity of the SVC capacitor branch.

Similarly, in the overvoltage range, the SVC characteristic corresponds to that of a fixed reactor of $B_{S_{max}}$ capacity with:

$$I_{SVC} = B_{S_{max}} v_t \tag{3.10}$$

Out of three modes of operation, the most desirable part of voltage regulation characteristic to be utilized in the operation of the compensator is the nominal control range. The rest of the two modes are seldom used [100].

The reactive power injected at bus $m$, by the SVC is expressed as:

$$Q_{SVC} = Q_m = -v_t^2 B_{SVC} \tag{3.11}$$

When, $B_{SVC}$ is considered as a state variable, the linearized form of the SVC can be represented as:

$$\begin{bmatrix} \Delta P_k \\ \Delta Q_k \end{bmatrix}^{(i)} = \begin{bmatrix} 0 & 0 \\ 0 & Q_k \end{bmatrix}^{(i)} \begin{bmatrix} \Delta \theta_k \\ \Delta B_{SVC}/B_{SVC} \end{bmatrix}^{(i)} \tag{3.12}$$

The value of SVC susceptance after $i^{th}$ iteration can be given as:

$$B_{SVC}^{(i)} = B_{SVC}^{(i-1)} + \left[\frac{\Delta B_{SVC}}{B_{SVC}}\right]^{(i)} B_{SVC}^{(i-1)} \tag{3.13}$$

This susceptance describes the overall SVC susceptance required to sustain the bus voltage magnitude at the specific value.

## 3.4 THYRISTOR CONTROLLED SERIES COMPENSATOR (TCSC) WORKING

This is one of the most widely used series compensation devices for controlling the flow of power in the transmission lines. TCSC controls the power flow in the transmission line, by manipulating the impedance of the line. This is done by introducing capacitors or inductors in series with the circuit. In maximum cases since the line is inductively loaded, the capacitive compensation is the most used. TCSC is having an upper hand over other conventional power system compensators as the latter constitute mechanical and moving parts. These parts are subject to wear and tear with time. On the other hand, TSCS constitutes a Thyristor-based static drive device that is free from such mechanical stress [102]. For the implementation of TCSC in a transmission line, $X_{TCSC}$ , a variable reactance is placed, in series to the line, representing the inductive or capacitive capacitance that the compensator has over the Line as shown in Figure 3.7.

### 3.4.1 TCSC Modeling

The power injection model of TCSC is shown in Figure3.8. At a steady-state, TCSC can change impedance magnitude by its governing approach. Here overcompensation of the line must be avoided. So, bounds suggested for the variation of reactance may be expressed by equation (3.14).

$$-0.8\, X_L \leq X_{TCSC} \leq 0.2\, X_L\, p.u. \tag{3.14}$$

In literature, the limits of the reactance are different for different systems. But limits for the capacitive reactance part larger than 50% of the total reactance of the line and inductive reactance part less than 25% of the total reactance of the line are sustained. To be used in a power system, the model must be with a built-in transformer reactance, to obtain the reactance variations introduced by the compensator expressed through the equation (3.14).

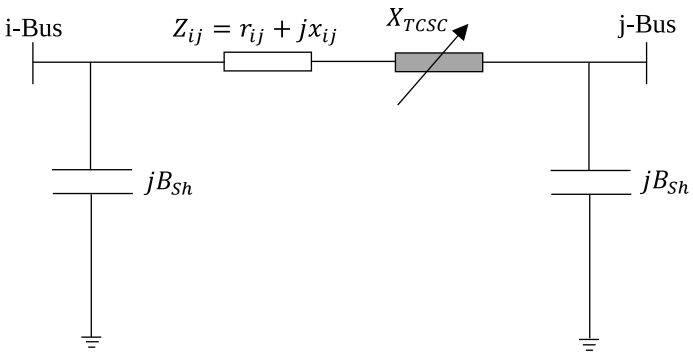

**Figure 3.7 Diagram of a transmission line compensated with TCSC [103]**

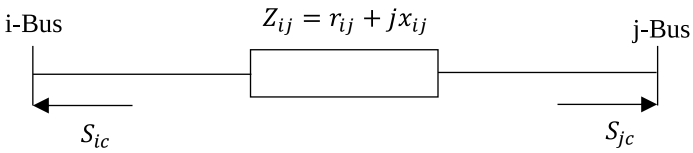

**Figure 3.8 TCSC Power Injection Model [87]**

$$\Delta y_{i,j} = y'_j - y_{i,j} = \left(G'_{i,j} + jB'_{i,j}\right) - (G_{i,j} + jB_{i,j}) \tag{3.15}$$

Here,

$$G_{i,j} + jB_{i,j} = \frac{1}{Z_{i,j}} \tag{3.16}$$

$$G_{i,j} = \frac{r_{i,j}}{r_{i,j}^2 + x_{i,j}^2}, G_{i,j} = \frac{-x_{i,j}}{r_{i,j}^2 + x_{i,j}^2} \tag{3.17}$$

$$G'_{i,j} = \frac{r_{i,j}}{r_{i,j}^2 + \left(x_{i,j} + x_{TCSC}\right)^2}, G'_{i,j} = \frac{-\left(x_{i,j} + x_{TCSC}\right)}{r_{i,j}^2 + \left(x_{i,j} + x_{TCSC}\right)^2} \tag{3.18}$$

Due to the series compensator, line admittance of the transmission system is changed as can be seen from equation (3.15). Change in admittance changes the admittance matrix as shown in equation (3.19)

$$Y'_{BUS} = Y_{BUS} + \left[\begin{array}{ccccccc} 0 & 0 & 0 & \cdots & 0 & 0 & 0 \\ 0 & \Delta y_{i,j} & 0 & \cdots & 0 & -\Delta y_{i,j} & 0 \\ 0 & 0 & 0 & \cdots & 0 & 0 & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & 0 & \cdots & 0 & 0 & 0 \\ 0 & -\Delta y_{i,j} & 0 & \cdots & 0 & \Delta y_{i,j} & 0 \\ 0 & 0 & 0 & \cdots & 0 & 0 & 0 \\ & & Col-i & \dots & Col-j & & \end{array}\right] \begin{array}{l} \\ \\ \\ Line-i \\ Line-j \\ \\ \\ \\ \end{array} \tag{3.19}$$

The active and reactive power flow in the transmission lines with TCSC connected, and the admittance got modified can be represented in equation (3.20) and (3.21)

$$P_{ijTCSC} = V_i^2 G'_{i,j} - V_i V_j [G'_{i,j} Cos(\delta_{ij}) - B'_{i,j} Sin(\delta_{ij}\ )] \tag{3.20}$$

$$Q_{ijTCSC} = -V_i^2 (B'_{ij} + B_{sh}) + V_i V_j [G'_{ij} Sin(\delta_{ij}) - B'_{ij} Cos(\delta_{ij})] \tag{3.21}$$

## 3.5 PROBLEM FORMULATION

From the literature survey, it has been estimated that the maximum power losses admissible to an electrical power system are 14% for its minimum economic operation. Due to the deregulation in the power market, the percentage of transmission and distribution losses has significantly increased. This made the power companies give a thought before thinking of investing in new transmission lines.

For a particular power system configuration, active power demand cannot be changed. The reduction in voltage deviation and power losses can only be achieved by reducing the decrease in reactive power transmission. For solving this problem reactive power compensation is one of the ways where shunt capacitors are connected to the transmission system. But this method is not preferable as it results in the circulation of a strong reactive current. The optimization method used to compensate for reactive power, mainly optimizes the choice of a capacitor, their locations, and the duration to which the capacitors are online. These techniques are chosen so that these may optimize the power flow reducing the power loss and maintaining the economy of transmission. The objective function can represent as follows:

**Objective function with TCSC**

$$\min(P+Q) = fun(loc, TCSCsize) \tag{3.22 a}$$

$$sub.to\begin{cases} 1 \le loc \le \max line\,number \\ -0.8X_L \le X_{TCSC} \le 0.2X_L \end{cases}$$

**Objective function with SVC**

$$\min(P+Q) = fun(loc, SVCsize) \tag{3.22 b}$$

$$sub.to\begin{cases} 1 \le loc \le \max BUS\,number \\ -0.25pu \le SVC_{size} \le 0.25pu \end{cases}$$

Where, $P$=Active power loss, $Q$=Reactive power loss, $loc$ =location, $tcscsize$=size of device

## 3.6 NEWTON-RAPHSON TECHNIQUE FOR LOAD FLOW ANALYSIS

Let us assume that:

$$S_i = I_i^* V_i \tag{3.23}$$

$$I_i^* = \sum_{m=1}^{n} Y_{im}{}^* V_m^* \tag{3.24}$$

$$Y_{im} = \rho_{im} + j\beta_{im} \tag{3.25}$$

The active power variation basically depends upon the change in phase angle $\delta$ while having little or no effect of change in voltage. On the other hand, the reactive power variation depends upon the change in the voltage while no effect of change in phase angle.

The elements of the Jacobian matrix, $J_{PV}$ can be calculated as:

$$\frac{\partial P_i}{\partial |V_j|} = |V_i|.\left|Y_{ij}\right|.\cos\left(\theta_{ij} - \delta_i + \delta_j\right) \tag{3.26}$$

Assuming that $\theta_{ij} \approx 90° \; and \; \delta_i \approx \delta_j$

Then,

$$\frac{\partial P_i}{\partial |V_j|} \approx |V_i|.\left|Y_{ij}\right|.\cos\text{ }(90°)\text{=}0.0$$

Now, we calculate the elements of the Jacobian matrix, $J_{Q\delta}$:

$$\frac{\partial Q_i}{\partial |\delta_j|} = -|V_i|.\left|V_j\right|.\left|Y_{ij}\right|.\cos\left(\theta_{ij} - \delta_i + \delta_j\right) \tag{3.27}$$

Again as $\theta_{ij} \approx 90°\ and\ \delta_i \approx \delta_j$

Then,

$$\frac{\partial Q_i}{\partial |\delta_j|} \approx -|V_i|.\left|V_j\right|.\left|Y_{ij}\right|.\cos(90°)\text{= }0.0$$

Therefore, the sub-matrices of the Jacobian $J_{Q\delta}$ and $J_{PV}$ are null matrices

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{P\gamma} & 0 \\ 0 & J_{QV} \end{bmatrix} . \begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} \tag{3.28}$$

Therefore, incremental change in active and reactive power can be calculated as:

$$\left.\begin{array}{r} \Delta P = J_{P\delta}.\Delta\delta = \frac{\partial P}{\partial \delta}.\Delta\delta \\ \Delta Q = J_{QV}.\Delta|V| = \frac{\partial Q}{\partial |V|}.\Delta|V| \end{array}\right\} \tag{3.29}$$

The elements of the Jacobian matrix, $J_{P\delta}$ are calculated:

$$\frac{\partial P_i}{\partial \delta_i} = \sum_{\substack{j= \\ j\neq i}}^{N} |V_i|.\left|V_j\right|.\left|Y_{ij}\right|.\sin\left(\theta_{ij} - \delta_i + \delta_j\right)$$

$$= -|V_i|^2.|Y_{ii}|.\sin(\theta_{ii}) + \sum_{\substack{j= \\ j\neq i}}^{N} |V_i|.\left|V_j\right|.\left|Y_{ij}\right|.\sin\left(\theta_{ij} - \delta_i + \delta_j\right) \tag{3.30}$$

here,

$$\frac{\partial P_i}{\partial \delta_i} = -|V_i|^2.|Y_{ii}|.\sin(\theta_{ii}) - Q_i \tag{3.31}$$

And

$$Q_i = \sum_{j=}^{N} |V_i|.\left|V_j\right|.\left|Y_{ij}\right|.\sin\left(\theta_{ij} - \delta_i + \delta_j\right) \tag{3.32}$$

$$|Y_{ii}|.\sin(\theta_{ii}) = B_{ii}, \qquad B_{ii} \gg Q_I$$

$$\frac{\partial P_i}{\partial \delta_i} = -|V_i|^2 . B_{ii}$$ and

$$|V_i|^2 = |V_i|$$

So, $$\frac{\partial P_i}{\partial \delta_i} = -|V_i| . B_{ii}$$

Now we calculate $\frac{\partial P_i}{\partial \delta_j}$

$$\frac{\partial P_i}{\partial \delta_j} = -|V_i| . |V_j| . |Y_{ij}| . \sin(\theta_{ij} - \delta_i + \delta_j) \tag{3.33}$$

Since $\delta_j - \delta_i \approx 0$, therefore,

$$\frac{\partial P_i}{\partial \delta_j} = -|V_i| . |V_j| . |Y_{ij}| . \sin(\theta_{ij}) \tag{3.34}$$

Where, $|Y_{ij}| . \sin(\theta_{ij}) = B_{ij}$, $|V_j| \approx 1$

$$\frac{\partial P_i}{\partial \delta_j} = -|V_j| . B_{ij} \tag{3.35}$$

The elements of the Jacobian matrix, $J_{QV}$ are calculated:

$$\frac{\partial Q_i}{\partial |V_i|} = -2. |V_i| . |Y_{ii}| . \sin(\theta_{ii}) - \sum_{\substack{j=1 \\ j \neq i}}^{n} |V_j| . |Y_{ij}| . \sin(\theta_{ij} - \delta_i + \delta_j) \tag{3.36}$$

$$\frac{\partial Q_i}{\partial |V_i|} = -|V_i| . |Y_{ij}| . \sin(\theta_{ii}) - |V_i|^{-1} \sum_{j=1}^{n} |V_i| . |V_j| . |Y_{ij}| . \sin(\theta_{ij} - \delta_i + \delta_j) \tag{3.37}$$

$$\frac{\partial Q_i}{\partial |V_i|} = -|V_i| . |Y_{ii}| . \sin(\theta_{ii}) - |V_i|^{-1} . Q_i \tag{3.38}$$

Where, $$Q_i = -\sum_{j=1}^{n} |V_i| . |V_j| . |Y_{ij}| . \sin(\theta_{ij} - \delta_i + \delta_j)$$

$$|Y_{ii}| . \sin(\theta_{ii}) = B_{ii} , \qquad B_{ii} \gg Q$$

$\frac{\partial Q_i}{\partial |V_i|} = -|V_i|. B_{ii}$ and

$$\frac{\partial Q_i}{\partial |V_j|} = -|V_i|. |Y_{ii}|. \sin (\theta_{ij} - \delta_i + \delta_j) \tag{3.39}$$

Since $\delta_j - \delta_i \approx 0$, therefore,

$$\frac{\partial Q_i}{\partial |V_j|} = -|V_i|. |Y_{ii}|. \sin (\theta_{ij}) \tag{3.40}$$

Where, $|Y_{ii}|. \sin (\theta_{ij}) = \mathrm{B_{ii}}$, $\frac{\partial Q_i}{\partial |V_j|} = -|V_i|. B_{ii}$

The individual power change equations in $J_{P\delta}$ and $J_{QV}$ are:

$$\Delta P_i = \sum_{J=1}^{N} -|V_i|. B_{ij}. \Delta\delta_j$$

$$\Rightarrow \frac{\Delta P_i}{|V_i|} = \sum_{J=1}^{N} -B_{ij}. \Delta\delta_j \tag{3.41}$$

$$\Delta Q_i = \sum_{J=1}^{N} -|V_i|. B_{ij}. \Delta|V_j|$$

$$\Rightarrow \frac{\Delta Q_i}{|V_i|} = \sum_{J=1}^{N} -B_{ij}. \Delta|V_j| \tag{3.42}$$

$$\frac{\Delta P}{|V_i|} = -B'. \Delta\delta$$

$$\Rightarrow \Delta\delta = -[B']^{-1}. \frac{\Delta P}{|V_i|} \tag{3.43}$$

$$\frac{\Delta Q_i}{|V_i|} = -B''. \Delta|V|$$

$$\Rightarrow \Delta|V| = -[B'']^{-1}. \frac{\Delta Q_i}{|V_i|} \tag{3.44}$$

## 3.7 CALCULATION OF REAL AND REACTIVE POWER LOSSES

### 3.7.1 Real Power Loss

Considering a simple system as shown in Figure 3.9, with a generator connected to a single load with a transmission line.

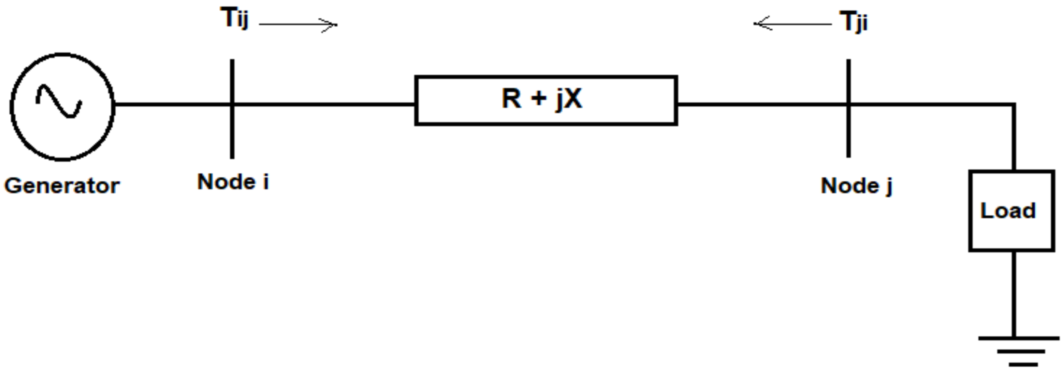

**Figure 3.9 A simple two bus test system for real power loss calculation**

Also, assuming the bus *i* as a node the real power $T_{ij}$ directed out of node *i*, can be represented as:

$$T_{ij} = re\{(V_i, \theta_i) * I^*\} \tag{3.45}$$

Here, $I^*$ is the complex conjugate of current flowing between two nodes *i* and *j* and can be represented mathematically as:

$$I^* = \left(\frac{(V_i,\theta_i)-(V_j,\theta_j)}{R_{ij}+jX_{ij}}\right)^* \tag{3.46}$$

In equation (3.46) the denominator represents the impedance of the line seen between the two buses *i* and *j*. As we are solving the power flow equations considering admittances so,

$$\frac{1}{R_{ij}+jX_{ij}} = G_{ij} - jB_{ij} \tag{3.47}$$

From equation (3.46) and (3.47) the real power flow now can be re-written as:

$$T_{ij} = re\left\{(V_i, \theta_i)\left(\frac{(V_i,\theta_i)-(V_j,\theta_j)}{R_{ij}+jX_{ij}}\right)^*\right\} \tag{3.48}$$

By applying equation (3.48)

$$T_{ij} = re\left\{(V_i, \theta_i)\left((V_i, -\theta_i) - (V_j, -\theta_j)\left(G_{ij} - jB_{ij}\right)\right)\right\} \tag{3.49}$$

$$T_{ij} = \left\{\left(V_i^2 - V_iV_j\left(\theta_i - \theta_j\right)\right)\left(G_{ij} - jB_{ij}\right)\right\} \tag{3.50}$$

Equation (3.50) can be written in a conventional form as:

$$T_{ij} = V_i^2 G_{ij} - V_iV_j\left\{G_{ij}cos\left(\theta_i - \theta_j\right) + B_{ij}sin\left(\theta_i - \theta_j\right)\right\} \tag{3.51}$$

Now the real power flowing from bus j to bus i can be represented as:

$$T_{ji} = V_j^2 G_{ij} - V_iV_j\left\{G_{ij}cos\left(\theta_i - \theta_j\right) - B_{ij}sin\left(\theta_i - \theta_j\right)\right\} \tag{3.52}$$

The real power loss on the line between bus i and bus j can now be calculated as:

$$\begin{aligned} P_L &= T_{ij} + T_{ji} \\ &= G_{ij}(V_i^2 - 2V_iV_j\cos\left(\theta_i - \theta_j\right) + V_j^2 \\ &= G_{ij}\left\{V_i^2 - 2V_iV_j\left(1 - \frac{\left(\theta_i - \theta_j\right)^2}{2}\right) + V_j^2\right\} \end{aligned}$$

$$P_L = G_{ij}\left\{\left((V_i - V_j\right)^2 + V_iV_j\left(\theta_i - \theta_j\right)^2\right\} \tag{3.53}$$

Considering the bus voltage magnitude at its nominal value i.e., $V_i = V_j = 1\ p.u.$ Then, the real power loss in the line can be written as:

$$P_L = G_{ij}\left\{\left(\theta_i - \theta_j\right)^2\right\} \tag{3.54}$$

Thus, in matrix form the real power loss can be written as:

$$[P_L] = \left[\theta_{ij}\right]^T\left[B_{ij}\right]\left[\theta_{ij}\right] \tag{3.55}$$

Equation (3.55) shows that the active power loss is directly proportional to the change in the voltage angles between two connected buses.

### 3.7.2 Reactive Power Loss

The same approach is adopted for calculating reactive power losses as was adopted for real power loss calculation. Considering the reactive power transfer between buses i and j of the system shown in Figure 3.10.

Let $Q_{ij}$ be the reactive power flow from bus i to bus j. mathematically it can be represented as

$$Q_{ij} = imj\{(V_i, \theta_i) * I^*\} \tag{3.56}$$

$$Q_{ij} = imj\{V_i, \theta_i * [(V_i, -\theta_i) - (V_j, -\theta_j)](G_{ij} + jB_{ij})\} \tag{3.57}$$

$$Q_{ij} = imj[\{V_i^2 - V_iV_j(\theta_i - \theta_j)(G_{ij} + jB_{ij})\}] \tag{3.58}$$

On simplifying (3.58)

$$Q_{ij} = V_i^2 B_{ij} - V_iV_j(B_{ij}cos\theta_{ij} + G_{ij}sin\theta_{ij}) \tag{3.59}$$

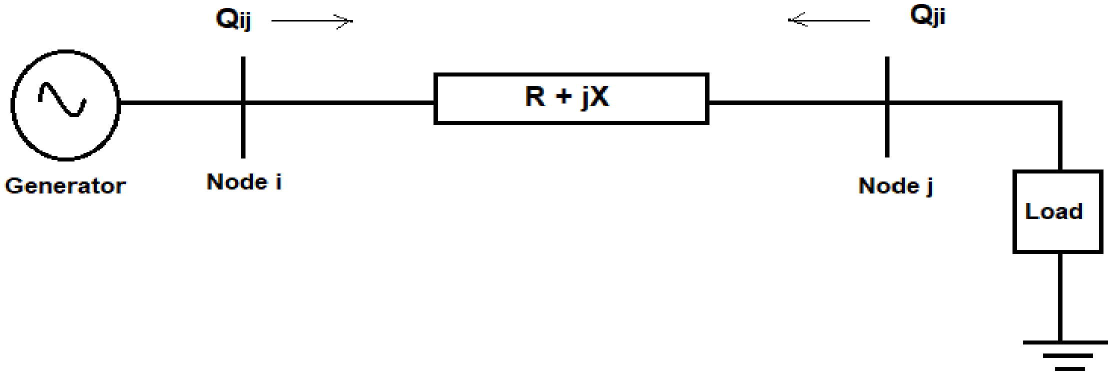

**Figure 3.10 A simple two bus test system for reactive power loss calculation**

Now the reactive power flowing from bus j to bus i can be written as

$$Q_{ji} = V_j^2 B_{ij} - V_iV_j(B_{ij}cos\theta_{ij} - G_{ij}sin\theta_{ij}) \tag{3.60}$$

Here, $\theta_{ij}$=$\theta_i$-$\theta_j$

Thus,

$$Q_L = B_{ij}\left(V_i^2 - 2V_iV_j cos\theta_{ij} + V_j^2\right) \tag{3.61}$$

$$Q_L = B_{ij}\left(\left(V_i - V_j\right)^2 + V_iV_j\theta_{ij}^2\right) \tag{3.62}$$

Equation (3.62) clearly shows that the reactive power losses are directly related to the changes in voltage magnitudes.

## 3.8 OPTIMAL LOCATION USING GREY WOLF OPTIMIZATION

The location and sizing of the FACT device for any specific bus system are optimized by Grey Wolf Optimization (GWO) [104]. The objective function is minimized using this technique. GWO mimics the social hierarchy of grey wolves. Apart from many special social behaviour, hunting is one of the important behaviour utilized in this algorithm. This behaviour can be explained in three main segments encompassing, chasing, and attacking. There are three social categories in a wolf pack. The pack is led by Alpha wolf, α. The next hierarchy consists of the beta wolf, β, and the lower gamma wolf, γ. When applying the algorithm, α is considered as the best position near the solution while β and γ are considered as second and third best fitness positions respectively. All the other wolves of the pack follow these 3 wolves during the entire hunting process. Upon the location of the prey, the grey wolves encircle it and harass the prey. This continues till the prey is exhausted and becomes still at a location. This encompassing can be presented as [105]:

$$D^{\rightarrow} = |C^{\rightarrow} * X^{\rightarrow}_{-prey}(t) - X^{\rightarrow}\_GW(t)| \tag{3.63}$$

$$X^{\rightarrow}_{-GW}(t+1) = X^{\rightarrow}_{-prey}(t) - A^{\rightarrow} * D^{\rightarrow} \tag{3.64}$$

here t designates the existing location of the grey wolf, vector $X^{\rightarrow}$presents the position of the prey, vector $X^{\rightarrow}\_{GW}$ denotes the position of the grey wolf

A & C are coefficient vectors which can be calculated as:

$$\left.\begin{array}{c}\vec{A} = 2\vec{a} * \vec{r}_1 - \vec{a} \\ \vec{C} = 2 * \vec{r}_2\end{array}\right\} \quad (3.65)$$

Here attraction coefficient ‘a’ reduces from 2 to 0 during the process of calculation and $\vec{r}_1, \vec{r}_2$ are some arbitrary values lying between 0 and 1.

The equations obtained while modeling the power system are exceptionally non-linear. Hence its solution can’t be obtained by traditional mathematical methods. So, the specific searching behavior of a pack of Grey wolves is replicated mathematically to trace the location of prey i.e., solution. The Top, three positions of the wolf obtained after a series of iterations are considered the best fitness values. These positions are considered to be taken by Alpha, Beta & gamma after being sorted and the location of the remaining wolfs is updated with respect to the current positions of alpha, beta & gamma wolfs. This can be mathematically realized as:

$$\left.\begin{array}{l}\vec{X}_1 = \vec{X}_{-\alpha}(t) - \vec{A}_1 * \vec{D}\_a \\ \vec{X}_2 = \vec{X}_{-\beta}(t) - \vec{A}_1 * \vec{D}\_b \\ \vec{X}_3 = \vec{X}_{-\gamma}(t) - \vec{A}_1 * \vec{D}\_g\end{array}\right\} \quad (3.66)$$

Where $\vec{D}\_\alpha\ \vec{D}\_\beta\ \vec{D}\_g$ are defined as:

$$\left.\begin{array}{l}\vec{D}\_a = |C * \vec{X}_{-\alpha}(t) - \vec{X}_{GW}(t)| \\ \vec{D}\_b = |C * \vec{X}_{-\beta}(t) - \vec{X}_{GW}(t)| \\ \vec{D}\_g = |C * \vec{X}_{-\gamma}(t) - \vec{X}_{GW}(t)|\end{array}\right\} \quad (3.67)$$

The average of the arithmetic summation of the top three locations of wolves provides the best location of the grey wolf:

$$X_{GW}(t+1) = \frac{\vec{X}_1 + \vec{X}_2 + \vec{X}_3}{3} \quad (3.68)$$

### 3.8.1 Pseudo Code for GWO Algorithm

```
//Initialization of the population//
generate X
```

```
initialize parameter a
Initialize vector coefficients A & C
appraise X (0);
get new (α, β, γ, X (0));
for e = 1 to $FVAL_{MAX}$ to do
    for all Wolf w in Omega do
        for i = 0 to DIM do
apprise location (w, i); // Updation of existing location
        end for
Alter the parameters (a, A, c); // alter the algo parameters
appraise X (e + 1);
choose new (α, β, γ, X (e + 1));
                e = e + 1;
        end for
end for
```

## 3.9 SIMULATION AND RESULTS

### 3.9.1 Results for IEEE-30 Bus Systems

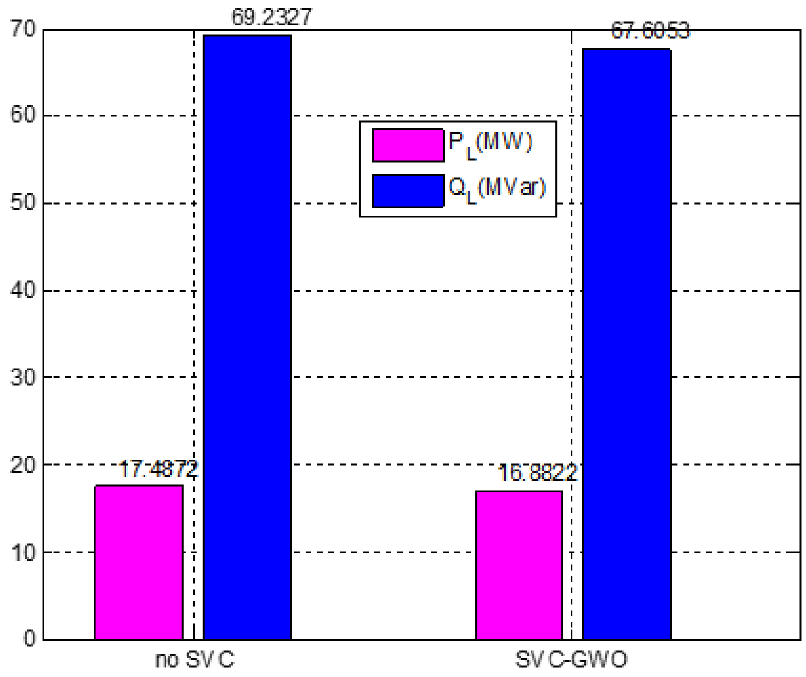

**Figure 3.11 Comparative analysis for $P_L$ and $Q_L$ with and without SVC and GWO**

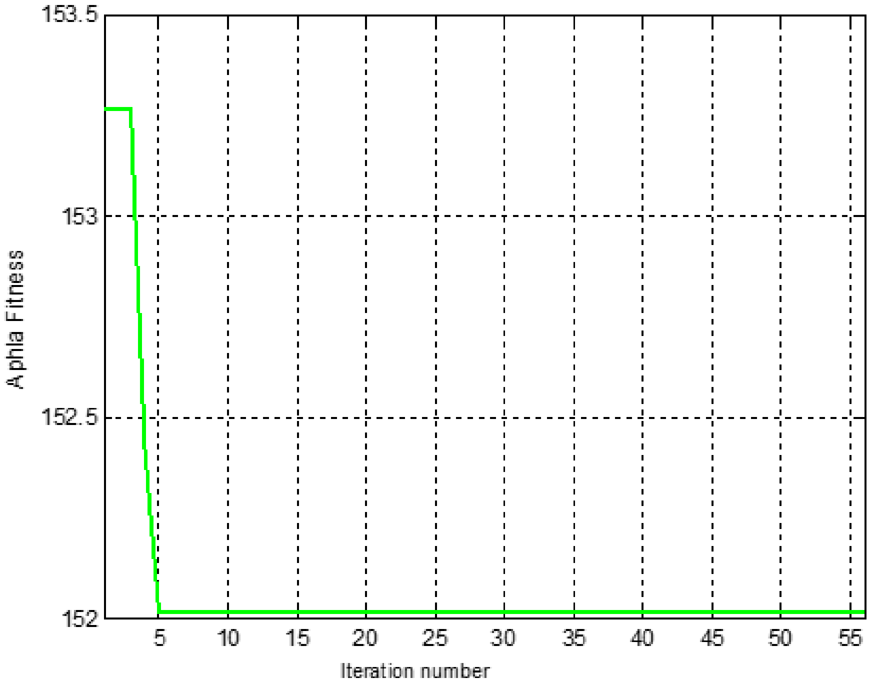

**Figure 3.12 GWO iteration graph with SVC**

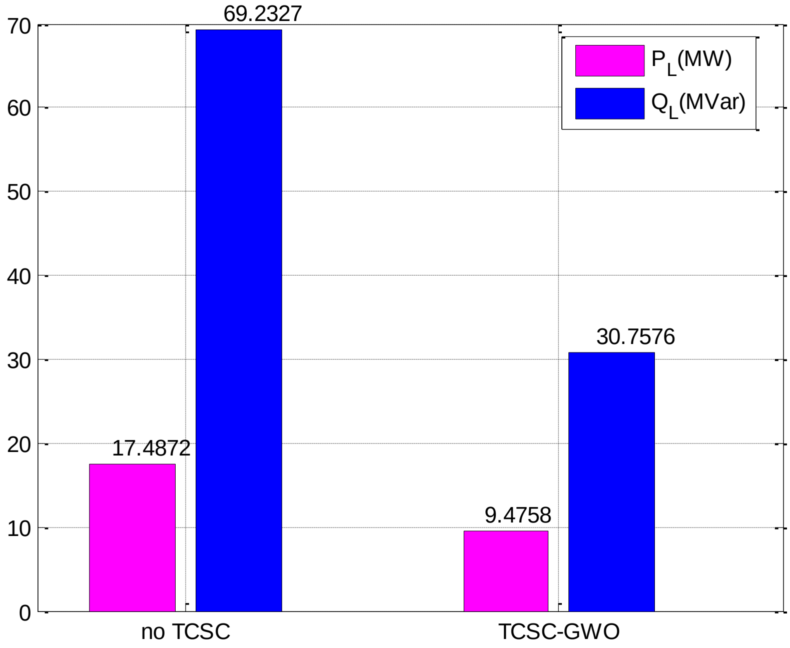

**Figure 3.13 Comparative analysis for $P_L$ and $Q_L$ with and without TCSC and GWO**

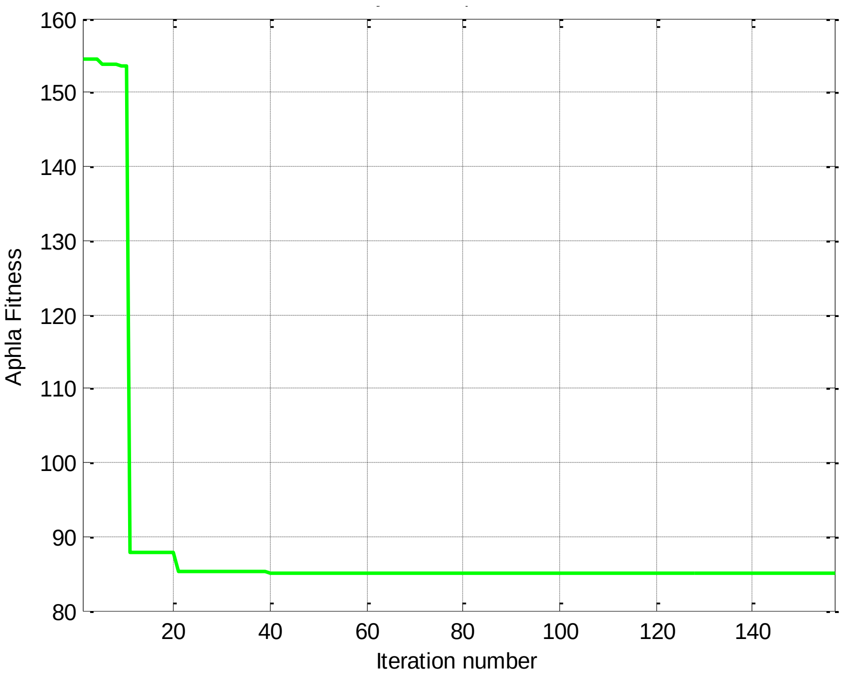

**Figure 3.14 GWO iteration graph with TCSC**

### 3.9.2 Results for IEEE-57 Bus Systems

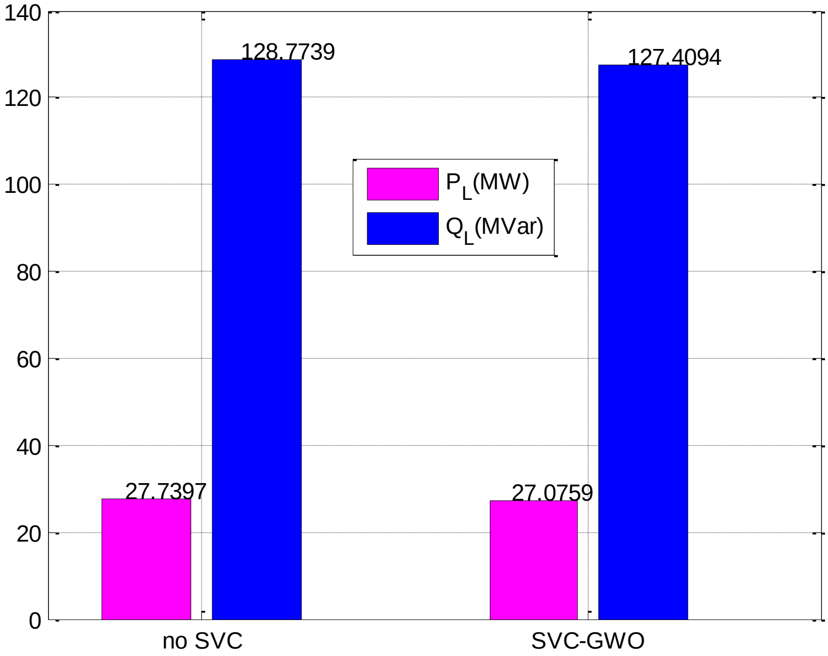

**Figure 3.15 Comparative analysis for $P_L$ and $Q_L$ with and without SVC and GWO**

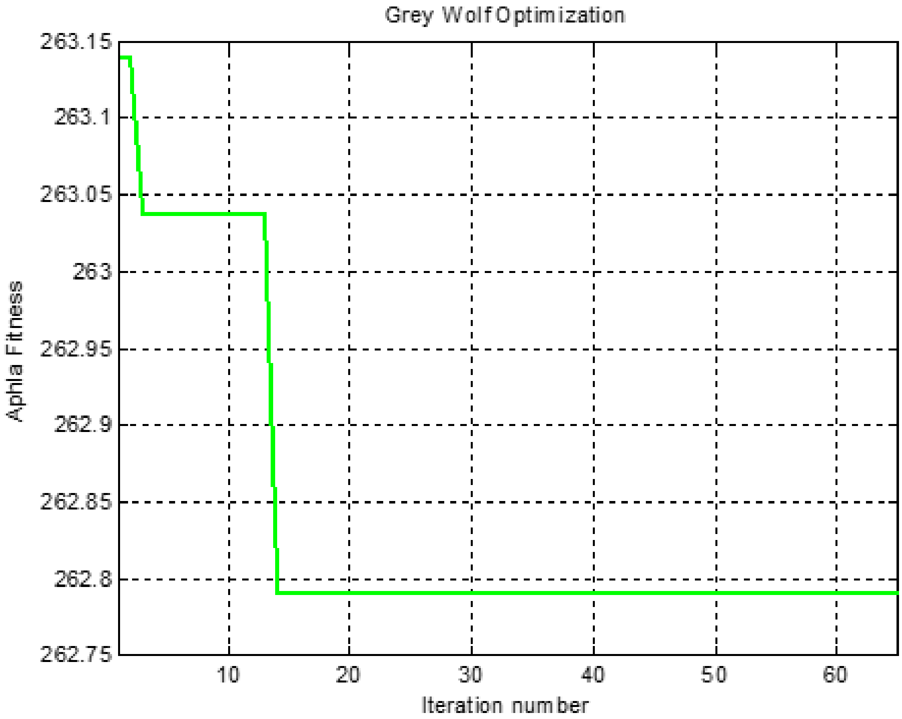

**Figure 3.16 GWO iteration graph with SVC**

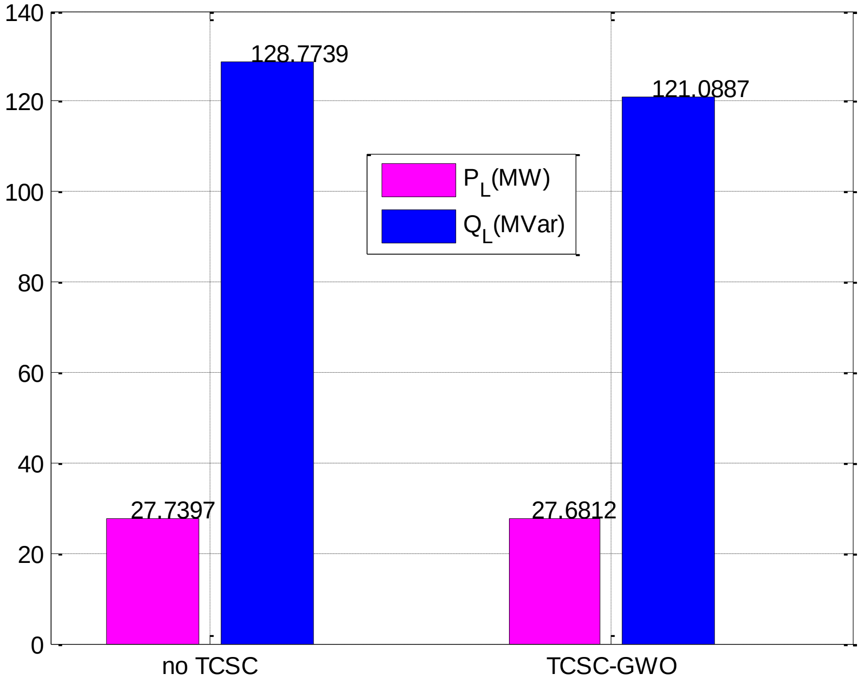

**Figure 3.17 Comparative analysis for $P_L$ and $Q_L$ with and without TCSC and GWO**

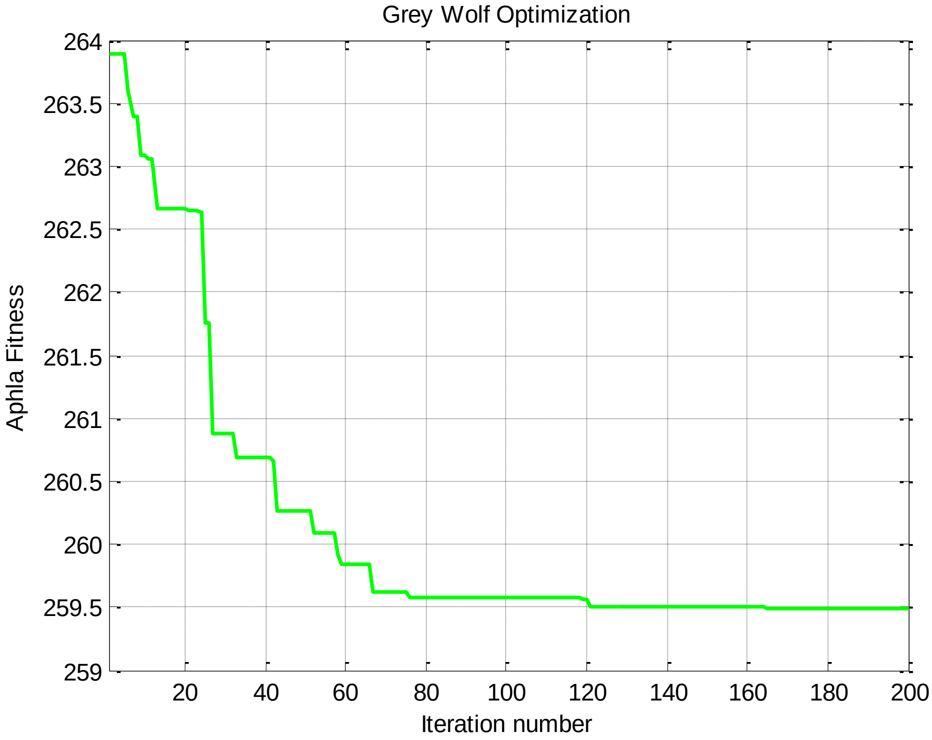

**Figure 3.18 GWO iteration graph with TCSC**

**Table 3.1 Comparison of active power loss and reactive power loss in IEEE-30 bus system with location and size of SVC and TCSC**

| **Losses** | **Without Device** | **With SVC GWO** | **Loc of SVC (Bus No.)** | **Bsvc** | **With TCSC GWO** | **Loc of TCSC (Line No.)** | **Xtcsc** |
|---|---|---|---|---|---|---|---|
| **$P_L$ (MW)** | 17.4872 | 16.8822 | 3 | 0.2473 | 9.4758 | 9 | -0.2615 |
| **$Q_L$ (MVAr)** | 69.2327 | 67.6053 | 3 | 0.2473 | 30.757 | 9 | -0.2615 |

**Table 3.2 Comparison of active power loss and reactive power loss in IEEE-57 bus system with location and size of SVC and TCSC**

| Losses | Without Device | With SVC GWO | Loc of SVC (Bus No.) | Bsvc | With TCSC GWO | Loc of TCSC (Line No.) | Xtcsc |
|---|---|---|---|---|---|---|---|
| **$P_L$ (MW)** | 27.7397 | 27.0759 | 16 | 0.2477 | 27.6812 | 18 | 0.2 |
| **$Q_L$ (MVAr)** | 128.7739 | 127.4094 | 16 | 0.2477 | 121.409 | 18 | 0.2 |

## CONCLUSION:

The active and reactive power losses are minimized here with the implementation of a series FACTS device, TCSC, and a shunt device, SVC. The two FACTS devices when optimized for location and parameter setting with the help of the GWO algorithm give a much more effective reduction in active and reactive power losses in the system as compared to the power losses in the system when no FACTS device is applied. A comparative analysis shows that TCSC optimized with GWO reduces the active power losses by about 45% as compared to 3.35% by SVC. Similarly, the reduction in reactive power loss is 55.58% with TCSC as compared to 2.35% with the implementation of SVC. Hence, here TCSC has played a significant role in reducing active and reactive power losses when optimized with GWO.

## CHAPTER IV

# FACTS DEVICE IMPLEMENTATION FOR ATC ENHANCEMENT TO MITIGATE CONGESTION

### 4.1 INTRODUCTION

Open access to power transmission is an important issue in most nations under deregulation of the power industry. Deregulation in the power system has brought competition to power generation industries. Restructuring of the power system has been beneficial in the aspect of reducing electricity charges and reliable power supply to the consumers. However, it has brought the menace of congestion. Sharing of power in interconnected systems has increased the reliability of the system. But with increased power transactions due to the utilization of interconnected systems, congestion came into existence resulting in transmission lines hitting voltage and thermal limits [106]. This condition can be averted by increasing the Available Transfer Capability (ATC) of the system. ATC calculation is one of the methods to discover congestion and mitigate any system from it. An evolutionary program has been given to enhance the power transferring capability in restructured power system [107]. An algorithm has been used to suggest the location & parameter setting of FACTS and also for the approximation of true power generated at the sending end. Sending end voltages with active power demand at the receiving end is also determined with this algorithm.

SSSC & UPFC being very flexible FACTS devices have been implemented in the power system to enhance system security. These devices when mathematically modeled manipulate the power equations of the system to increase the power flow. UPFC together with two coordinated VSCs can be connected in series & parallel with the help of transformers to improve power system security. FACTS devices when tuned for parameters setting and location by applying particular evolutionary programming, system losses are reduced with the enhancement of ATC [108]. With full capacity utilization of the existing transmission facility, the generators get maximum benefit even if the customer is charged at reduced rates [109]. Enhancement of ATC involves numerous manipulations in terms of generator terminal voltage and power output. ATC of any power system is dependent on its thermal limits, range of operating voltage, and stability conditions. This is due to the continuously changing operating conditions of the system. For calculation of the ATC value of any power system, total system load data with its transfer capabilities, distribution and operating limits constraints must be available to power market participants to participate in it. A steady-state analysis approach has been used with security-constrained optimal power flow (SCOPF) to steady-state security-constrained OPF for the calculation of ATC [110,111].

But as SCOPF is a long and time-consuming process, the work has been reported on Transfer Based SCOPF for ATC calculation in the deregulated environment [112]. A novel method for ATC formulation explaining the effects of reactive power flows, voltage fluctuation, and thermal loading effects has been proposed using continuation power flow (CPF). This method is fast for calculating ATC for successive power transfers while considering several contingencies. The proposed method considers the thermal limits only to apply linear incremental power flow approximation. ATC maximization has been reported using a sequential programming method for calculating optimal value ATC to maximize the summation of generated power and demand at the load end [113]. HOPF bifurcation limits have been used to determine dynamic ATC while static ATC and voltage limits were calculated by saddle-node bifurcation [114]. The method to train the neural network with Quick Prop Algorithm has been proposed using OPF. Load and generator status has been taken as input while transmission capacity was taken as output to the neural network. The method gave a quick solution when applied to calculate the multi-area power transfer capability of the power system [115]. A strategy with a multi-layered feed-forward system for ATC estimation has been proposed where the crossover rule is applied to eliminate the elementary transfer statistics for ISO [116]. GA has been implemented for evaluating Total Transfer Capacity. Global optimal search has been proposed in [117] where power transfer amid two areas was calculated within the system limitations.

## 4.2 FACTS DEVICE AND ITS APPLICATION

One of the cost-free and most competent methods to mitigate congestion is the application of a suitable type of FACTS device at an optimal location. As a fact, the voltage and thermal ratings of a power system determine the amount of power that can be transmitted securely and reliably through the system transmission lines. During heavily loaded conditions the power transmission lines are working near the rated thermal and voltage limits. This concerns the security of the system as the transmission cannot be maintained for longer durations. But with the implementation of FACTS, the sudden system changes can be rapidly acted upon to make the interconnected system operation secure and reliable [118]. The power system is designed with calculated thermal and voltage ratings for all the circuits and corresponding circuit elements. However, when the power flow analysis is done, the circuits and its element do not share their share of ratings. This results in a somewhat disturbing voltage profile. Thus, a heavily loaded line always restricts the ATC value of the system leaving behind the nodes at low voltages. When FACTS devices are optimized for their parameter and location, power flows in the system are redistributed so that the lines may not be subjected to undue stress. The voltage at nodes is also regulated by the FACTS near the optimum value by manipulating the line reactance and phase angles as the adjusting parameters [119]. With this manipulation in line reactance and voltage phase angles, the physical constraints of the line get changed and the system starts to transmit the power at updated and elevated thermal limits. The result of using FACTS devices in the system is that despite the costly employment of the device, the power system becomes more economical and efficient, as the need for expansion of the system framework is reduced.

The exceptional development in the field of power electronics assured reliability and high efficacy of FACTS in the current restructured power system. Therefore, enhanced loading of the power system in restructured power markets has necessitated the utilization of financially savvy technologies in form of FACTS to make the system more economical and controllable under different working conditions.

This chapter illustrates the allocation of series FACTS device TCSC with the help of ACPTDF as a sensitivity factor whereas the parameter is optimized by the application of GWO. The location and size of TCSC are such that it enhances the ATC value as one objective and reduces transmission power loss as another objective of the formulated multi-objective problem. The methodology to incorporate TCSC has authenticated on the IEEE 30-Bus system with the application of GWO.

## . 4.3 ATC CALCULATION

The power transfer capacity that is offered by the interrelated power system for further power utilization in other commercial activities above already committed uses is termed Available Transfer Capability (ATC). ATC is expressed as:

$$ATC = TTC - TRM - ETC - CBM$$

In the above expression,

$ETC$: existing transmission commitment

$ETC = \sum$ current transmission commitment among different areas.

The power that can be transferred into an interconnected system reliably is termed TTC (Total Transfer Capability). Figure 4.1 shows the limits that are implemented while calculating TTC.

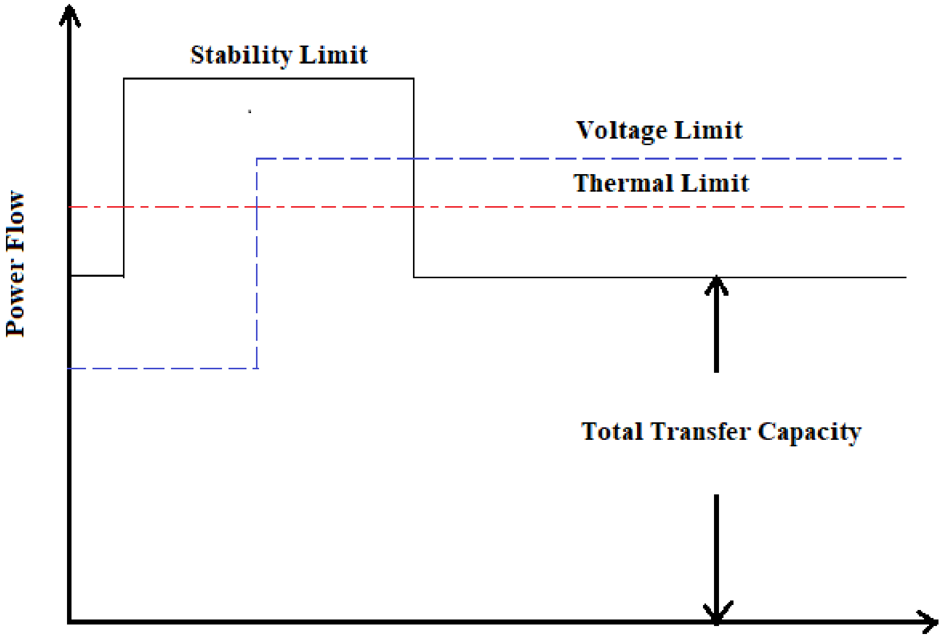

**Figure 4.1 Limiting Factors of Total Transfer Capacity**

The capability of a system to transfer power securely in an interconnected system when subjected to a number of pre-and post-studied contingency conditions is termed as Transmission reliability Margin (TRM).

Power transfer capability which is reserved by utilities at the load end, ensuring generation within defined reliability limits is called Capacity benefit Margin (CBM) [106]. Another term related to ATC is recallability, which in turn is the entitlement of the service provider to terminate the power supply for any reason including economic loss which is within the provision of the contract. The right of a service provider to interrupt services when there is a compromise with the reliability of supply is called non-recallability. Thus,

Recallable ATC = [TTC-TRM-Recallable transmission -Non-recallable transmission with CBM] and

Non-Recallable ATC= [TTC-TRM-Non recallable Reserve with CBM].

With enhanced competition in power markets, the lines are continuously working under stressed voltage and thermal limits. So, ATC can be expressed as the ability of a system to relocate power from an over-loaded part of the system to an unstrained part in the same power system framework.

Figure 4.2 shows all the terms related to the calculation of Available Transfer Capacity ATC is related to some important terms:

- **Curtailability:** Curtailability is the right of a transmission provider to interrupt complete or partial transmission affected by the constraints which decrease the ability of the system to deliver the pre-decided transmission facility. System service is curtailed only when the constraints are adversely affecting the reliability of the system. As soon as the constraints are no longer restricting the capability of transmission, the services are resumed back to normal. This right to interrupt the transmission is not valid when the discontinuity is related to economic reasons.
- **Recallability:** Is the right of a service provider to cut complete or a fraction of transmission service for all reasons which also including economic. Here the right is consistent with the policy and the contract provisions between transmission providers and customers.

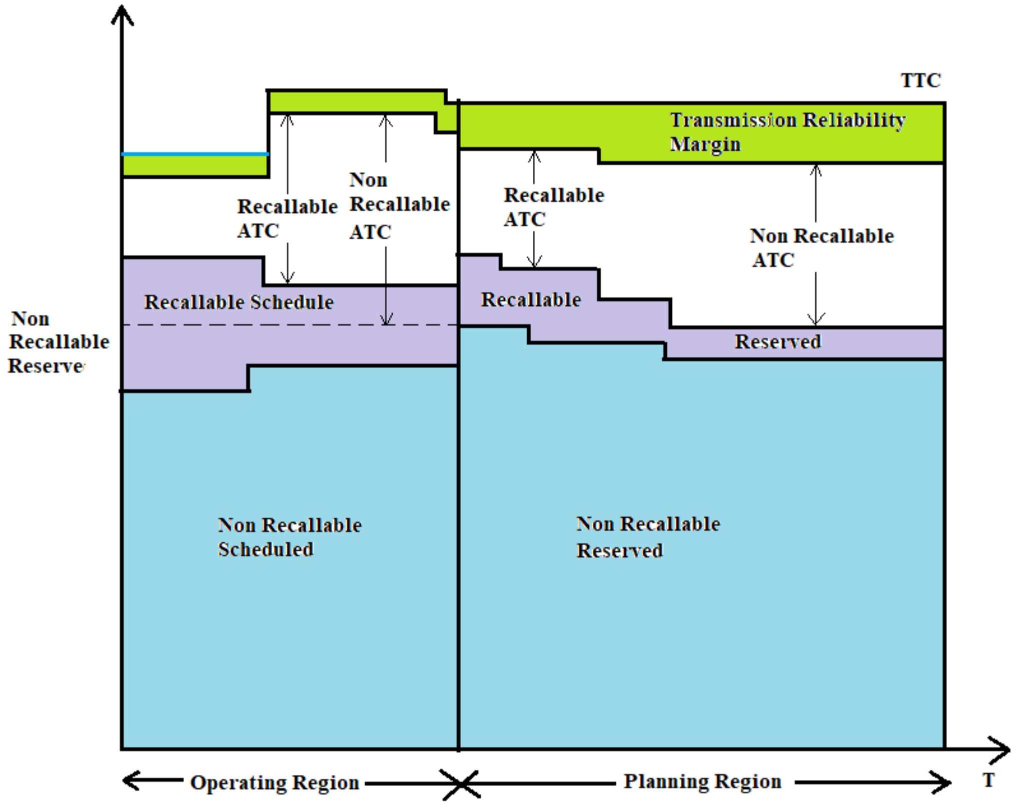

**Figure 4.2 Terms related to Available Transfer Capaci ty**

- **Non-recallable Available Transfer Capability**: NATC is TTC less the summation of TRM, non-recallable reserved transmission service which includes CBM. This is the maximum significant utilization of the network. The amount of non-recallable service which can be held in reserve is calculated based on the capacity that the network can consistently hold while subjected to normal operating conditions and also with proper contingencies as defined in NERC.
- **Recallable Available Transfer Capability**: Recallable ATC (RATC) is expressed as:

  RATC=TTC-TRM- recallable transmission service- less non-recallable transmission service (including CBM).

  A prespecified part of the TRM is available for recallable use by the transmission provider. This depends on the conditions at a particular time for providing extra transmission services. Part of CBM is made available for recallable use, it also depends upon the time frame under consideration for providing additional transmission service. RATC has the least priority use in the transmission network and is recallable following the notice requirements of the transmission service tariffs.

The sensitivity factor approach for the determination of ATC is simple and faster than other approaches to ATC calculation. This sensitivity factor used here is the Power Transfer Distribution Factor (PTDF) which relates actual power flow and the amount of power flowing in the line between two specified buses involved. There are two PTDF mentioned in the literature. The first one is DCPTDF, which is calculated with DC load flow with the following assumptions:

a) Line resistances are negligible as compared to reactance hence not considered in calculations.
b) The difference in voltage angles between the two buses is very small.
c) Reactive power flows are not considered.
d) Tap settings of the transformer are ignored.

These assumptions make the results very convergent but are not very accurate. So DCPTDF is not implemented here. The second sensitivity factor is the AC Power Transfer Distribution factor (ACPTDF) where actual AC load flow is performed. This factor relates to the change in system parameters under normal and contingency conditions, with the change in power transaction [120]. Hence, it measures the sensitivity of line active power flows to active power transfer through the line connected between buses i-j for bilateral active power transactions between bus m and bus n. Bus m is called seller bus while bus n is called buyer bus. Now ACPTDF can be given as [121].

$$ACPTDF_{ij,m} = \Delta P_{ij}/P_{mn} \tag{4.1}$$

Where $P_{mn}$ is the transacted power flow between seller bus m and buyer bus n.

$$\Delta P_{ij} = \left[\frac{\partial P_{ij}}{\partial V_i}\right]\Delta V_i + \left[\frac{\partial P_{ij}}{\partial V_i}\right]\Delta V_j + \left[\frac{\partial P_{ij}}{\partial \delta_i}\right]\Delta \delta_i + \left[\frac{\partial P_{ij}}{\partial \delta_i}\right]\Delta \delta_j \tag{4.2}$$

Equation (2) may be rewritten as:

$$\Delta P_{ij} = \begin{bmatrix} \frac{\partial P_{ij}}{\partial \delta_2} \cdots \frac{\partial P_{ij}}{\partial \delta_n} \frac{\partial P_{ij}}{\partial V_2} \cdots \frac{\partial P_{ij}}{\partial V_n} \end{bmatrix} * \begin{bmatrix} \partial \delta_2 \\ . \\ . \\ \partial \delta_n \\ \partial V_2 \\ . \\ . \\ \partial V_n \end{bmatrix} \tag{4.3}$$

$$\Delta P_{ij} = \begin{bmatrix} \frac{\partial P_{ij}}{\partial \delta_2} \cdots \frac{\partial P_{ij}}{\partial \delta_n} \frac{\partial P_{ij}}{\partial V_2} \cdots \frac{\partial P_{ij}}{\partial V_n} \end{bmatrix} * \begin{bmatrix} J1J2 \\ J3J4 \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ . \\ . \\ +Pt \\ 0 \\ . \\ . \\ -Pt \\ 0 \end{bmatrix} \tag{4.4}$$

The transfer of power through-line between *i-j* in the system due to active power transaction in the line between bus *m-n* is given as :

$$T_{ij,mn} = \begin{Bmatrix} \frac{\left(P_{ij}^{max} - P_{ij}^{0}\right)}{PTDF_{ij,mn}}; \quad PTDF_{ij,mn} > 0 \\ \alpha(inf\ i\ nite); PTDF_{ij,mn} = 0 \\ \frac{\left(-P_{ij}^{max} - P_{ij}^{0}\right)}{PTDF_{ij,mn}}\ ; \quad PTDF_{ij,mn} < 0 \end{Bmatrix} \tag{4.5}$$

here,

$P_{ij}^{max}$: denotes maximum real power flow limit through line *i-j*.

$P_{ij}^{0}$ : denotes base case real power flow through line *i-j*.

*PTDF ij, mn* is the PTDF for line i-j regarding the exchange between transport m and *n*

$$ATC_{mn} = min\{T_{ij,mn}\}, ij \in N_L \tag{4.6}$$

Here, $N_L$ is the total number of lines.

## 4.4 OPTIMAL POWER FLOW PROBLEM

**A**. Control Variables

- Control factors that have an expense:

  Real power generated by thermal units, $P_i^G$

- Control factors that don't have an expense:
  Voltage magnitude at the generation units, $V_i^G$
- Transformers tap ratio, $t_{ij}$

**B**. Objective functions

- Maximize the ATC

$$ATC_{pq} = \{T_{ij}\} \ \forall \ ij \in nl \tag{4.7}$$

- Minimize Total power loss:

$$TPL = \sum_{k=1}^{nl} g_k (V_i^2 + V_j^2 - 2V_iV_j \cos(\delta_i - \delta_j)) \tag{4.8}$$

**C**. Equality constraints

Power balance at each node bus, i.e., power flow equations.

$$\left.\begin{aligned} a)\ P_{gi} - P_{di} - P_i(V_i, \delta_i) = 0 \\ b)\ Q_{gi} - Q_{di} - Q_i(V_i, \delta_i) = 0 \end{aligned}\right\} \tag{4.9}$$

Where,

$Pgi$ represents the real power generation at $i_{th}$ bus

$Qgi$ denotes reactive power generations at $i_{th}$ bus,

$Pdi$ denotes active power demand at $i_{th}$ bus

$Qdi$ is the reactive power demand at $i_{th}$ bus.

$Vi$ & $\delta i$ are the voltage magnitudes and their respective phase angle at $i_{th}$ bus.

**D**. Inequality constraints

a) Generated active power limits: $p_{Gi}^{Min} \le p_{Gi} \le p_{Gi}^{Max}$
b) Generated reactive power limits: $Q_{Gi}^{Min} \le Q_{Gi} \le Q_{Gi}^{Max}$
c) Upper and lower voltage limits: $V_i^{min} \le V_i \le V_i^{max}$
d) TCSC reactance limits in p.u.: $-0.8X_L \le X_{TCSC} \le 0.2X_L$
e) Transformer TAP setting limits: $T_i^{min} \le T_i \le T_i^{max}$

Voltage limits at each node of the network are taken between 0.90 p.u. to 1.05 p.u., while generator terminal voltage is limited between 0.95 p.u. to 1.50 p.u. as per standards.

## 4.5 GREY WOLF OPTIMIZATION ALGORITHM

GWO replicates the chasing behavior and the social order of grey wolves. Apart from well-organized social hierarchies, well-planned pack chasing is an additional substantial social act of grey wolves. The main parts of GWO are surrounding, chasing, and attacking the prey. The flow chart for the GWO algorithm is explained in Figure 4.5. When applying the GWO algorithm, we consider alpha (α) wolf at the position with the best fitness value, and accordingly, the next two best positions are beta (β) and gamma (g). These wolves acquired the three best positions, and guide different wolves during searching.

***Grey Wolf Optimization Algorithm:***

1. *Initialization of population (n=100)*
2. *Read and initialize input data*
3. *Set parameters (a, A, C)*
4. *Set iteration count, iter=0*
5. *Appraise fitness value and assign top three values as* $\alpha$, $\beta$ & $\gamma$
6. *Reduce 'a' according to the equation from 2 to 0:*

$$a(iter) = 2 * iter_{count}(\frac{2}{Max\ Iter})$$

7. *Get updated values of A & C*
8. *Apprise the position vectors* $D_{\alpha}$, $D_{\beta}$ & $D_{\gamma}$
9. *Apprise place of every solution obtained*
10. *for the same position end,*
11. *else, increment iteration count to iter=iter+1and restart with Step 4.*

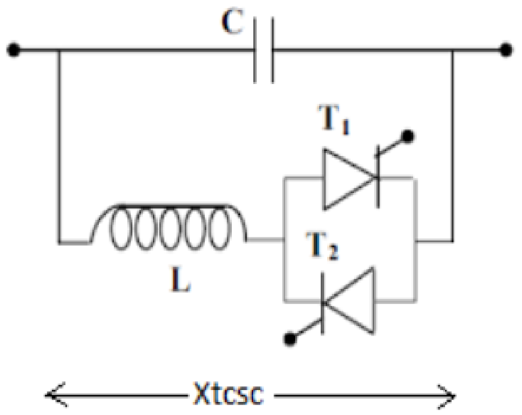

**Figure 4.3 A schematic diagram of TCSC device**

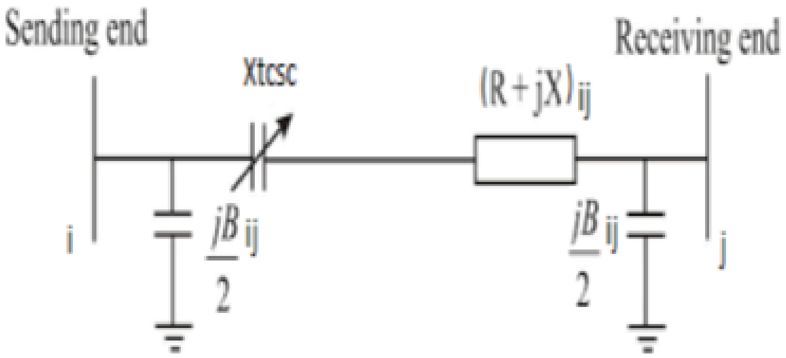

**Figure 4.4 Equivalent circuit of TCSC connected in Line**

## 4.6 POWER FLOW MODELING OF TCSC

Thyristor-controlled series compensator (TCSC) device is a series compensator which controls the power flow by manipulating the reactance of the line. Figure 4.3 and Figure 4.4 show the models of TCSC implemented in this chapter. Each capacitive and inductive reactance is done by proper selection of capacitor and inductor values of the TCSC device which is completed through the reactance equation.

Using the power injection model of TCSC [103]

$$\Delta Y_{ij} = y'_{ij} - y_{ij} = (G'_{ij} + jB'_{ij}) - (G_{ij} + B_{ij}) \tag{4.10}$$

$$G_{ij}{}' + jB_{ij}{}' G_{ij} + B_{ij} = \frac{1}{Y_{ij}} \tag{4.11}$$

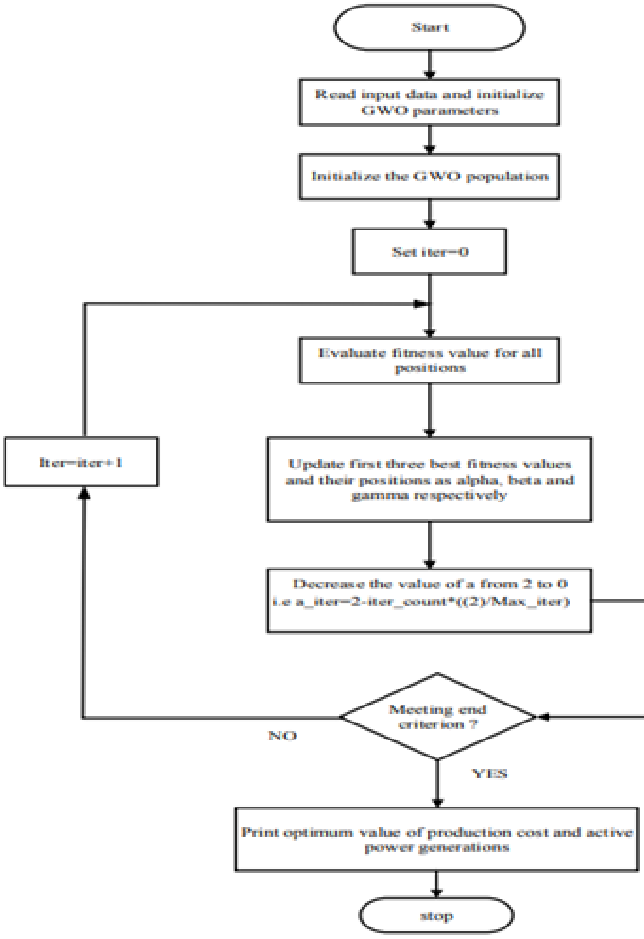

Figure.4.5 Flow Chart for GWO Algorithm [26]

$$G_{ij} = \frac{r_{ij}}{r_{ij}^2 + x_{ij}^2} \quad \& \quad B_{ij} = \frac{-x_{ij}}{r_{ij}^2 + x_{ij}^2} \tag{4.12}$$

Equation (4.10) represents the modification of the Y bus matrix which alters the elements of the Jacobian matrix used in the NR method. The power flow through the lines gets modified which can analytically be represented as:

$$P_{ij(tCSC)} = V_i^2 G_{ij}^{'} - V_i V_j [G_{ij}^{'} \, Cos(\, \delta_{ij}) - B_{ij}^{'} \, Sin(\, \delta_{ij})] \tag{4.13}$$

To achieve the objective of power loss minimization, GWO is employed to get the most optimal location and parameter setting of FACTS. NR load flow is carried out after

TCSC is connected in the line for different locations and line flows. Power loss for each case is calculated and sorted to get the location of TCSC giving the least value of power loss. The optimal location of TCSC is the one with the least power loss. After getting this location further ATC calculation is done by an assumption that the FACTS device is already being installed at a particular location.

## 4.7 METHODOLOGY APPLIED

The objective function constitutes of two objectives:

$$F(x) = h_1 * (ATC)\,max + h_2 * (TPL)min$$

The value of total weight factors must be equal to 1 i.e. $h_1 + h_2 = 1$

MATLAB software is used for the following programming.

**A) For Maximization of ATC:**

***With no TCSC***

1. GWO is applied for OPF with NR to get the line flows.
2. NR with OPF is applied after a bilateral transaction is done to get the updated power flows in lines.
3. Changes in real line flows are calculated by the line flows with a base case and without a bilateral transaction.
4. A transaction of 1MW is created to calculate ACPTDF with a change in real power flows.
5. ATC is now calculated by the obtained value of ACPTDF for a specific bilateral transaction between the seller and buyer bus for both the nearest bus and far away from the bus.

***With the implementation of TCSC***

1. The OPF is attained by applying GWO
2. The optimal location of TCSC is obtained by sensitivity factor and parameter setting with GWO.
3. After locating TCSC, OPF with NR is applied for calculating the line flows.
4. After a transaction between the seller and buyer-bus is done, OPF with NR is applied to get the updated Line flows
5. Change in real power flows is evaluated by the line flows attained with and

without the bilateral transaction.

6. ACPTDF values are calculated with the difference in real power flows and the transaction being created (i.e. 1MW)
7. Then for a particular bilateral transaction, ACPTDF is calculated and in turn, ATC values are evaluated for a specific transaction for nearby and for a far away situated bus.

### B) For Minimization of Total Power Loss (TPL)

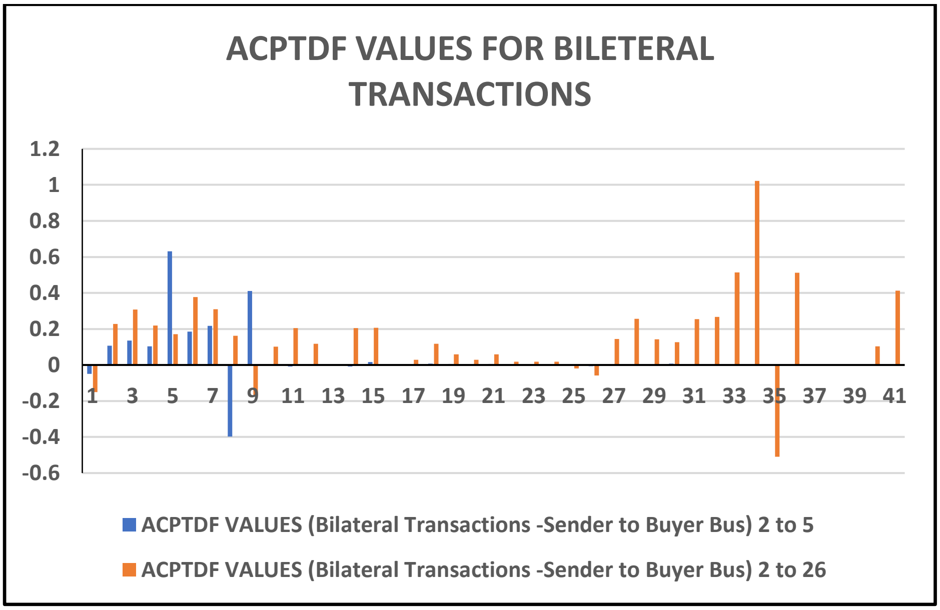

**Figure 4.6 ACPTDF values for Bilateral Transactions**

For the minimization of power loss, the same procedure is adopted with an objective to minimize TPL only. Here it can be observed that the value of ATC is decreased with the decline of TPL.

Figure 4.6 shows ACPTDF calculated using equation (4.1).

**Table 4.1 Consolidated results for OPF comparison between GWO and FA**

| Comparison of OPF for Transaction 2-26 | | |
|---|---|---|
| **Without Device** | | |
| **Control Variables** | **For ATC Maximization** | **For TPL Minimization** |

|  | **GWO** | **FA [104]** | **GWO** | **FA [104]** |
|---|---|---|---|---|
| $PG_1$ (MW) | 118.9856 | 119.9812 | 118.9856 | 119.3438 |
| $PG_2$ (MW) | 54.28698 | 63.6613 | 53.75598 | 74.2959 |
| $PG_5$ (MW) | 27.94923 | 31.8922 | 27.94923 | 28.2397 |
| $PG_8$ (MW) | 35 | 23.7808 | 35 | 17.7711 |
| $PG_{11}$ (MW) | 25.70227 | 26.3744 | 25.70227 | 21.9291 |
| $PG_{13}$(MW) | 28.48362 | 24.2911 | 28.48362 | 26.7144 |
| Total Generation (MW) | 290.4077 | 289.981 | 289.8767 | 288.294 |
| ATC (MW) | 12.1845 | 7.4715 | 12.18 | 7.4315 |
| TPL(MW) | 7.01 | 6.1819 | 6.493 | 4.8941 |

From Table 4.1 it can be clearly illustrated that GWO delivers promising OPF output even when FACTS are not employed in comparison to other algorithms.

## 4.8 RESULTS & DISCUSSIONS

Figure 4.7 depicts the standard IEEE 30-Bus system for validating the results.

Figure 4.8 depicts the deviation of ATC value for all the possible transactions with the generator at bus no 2. Here bus 2 is taken as seller bus and all the load buses are taken as buyer buses. It is clear from Figure4.8 that buses 2-5 are the nearest buses so ATC value is maximum, (116.5 MW) and the farthest buses i.e. 2-26 have the least value of ATC (12.18 MW).

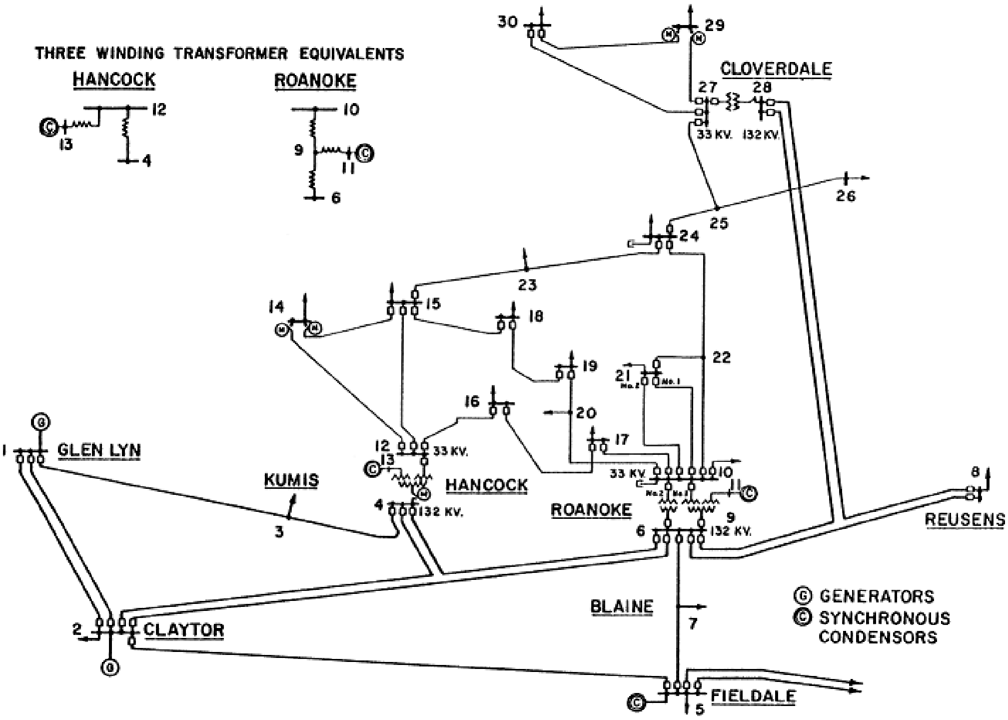

Figure 4.7 Standard IEEE 30-Bus System

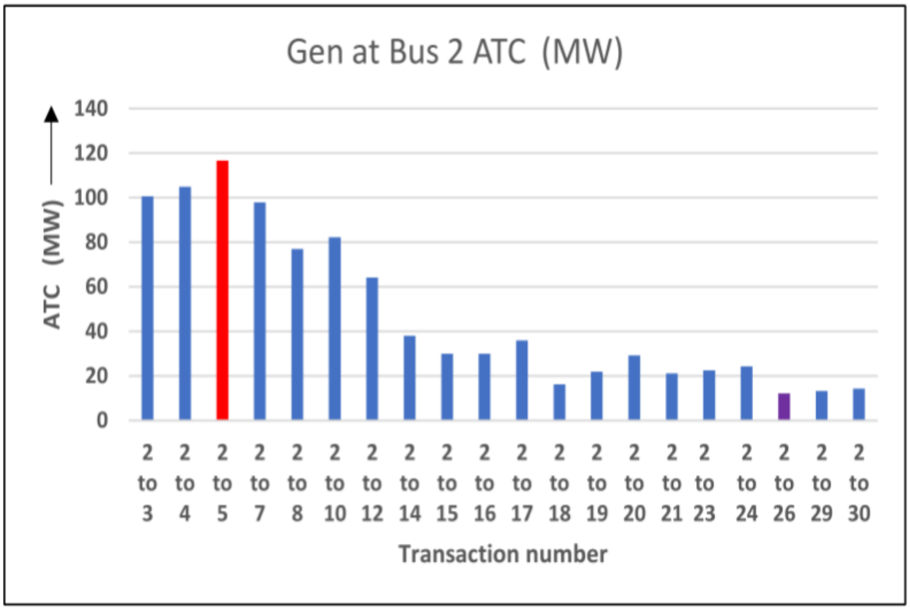

Figure 4.8 Alteration in ATC for all transactions with Gen-2

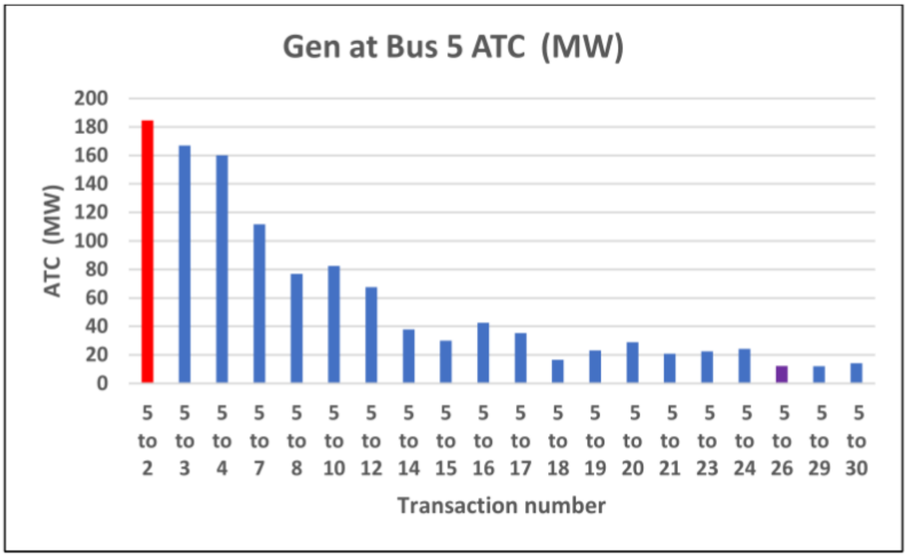

**Figure 4.9 Alteration in ATC for all transactions with Gen 5**

The distribution of ATC in the power system under consideration due to generator injections at bus number 5 can be depicted in Figure 4.9. The graph deduced that the ATC value is maximum (184.56 MW) between buses 5 to 2 which are the nearest buses and ATC is minimum (12.26 MW) between buses 5 to 26.

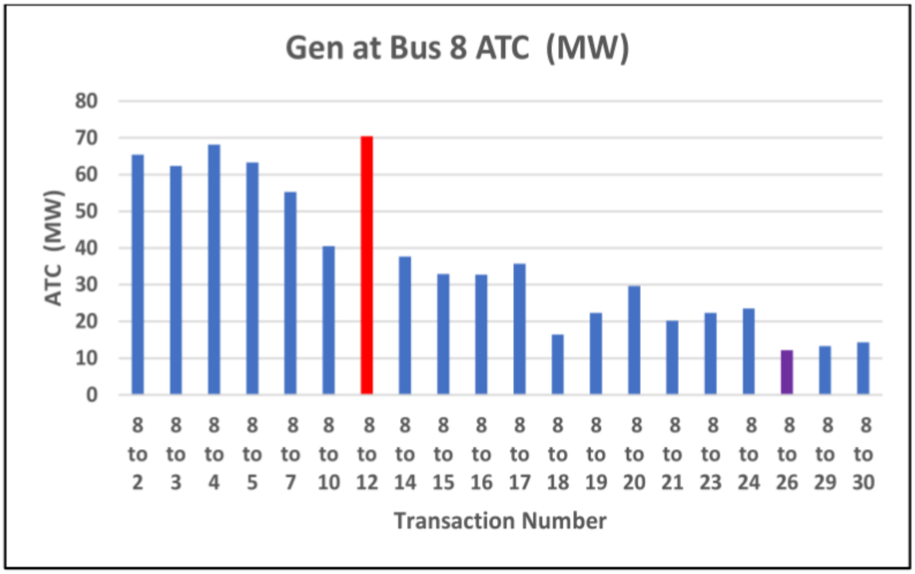

**Figure 4.10 Alteration in ATC for all transaction with Gen-8**

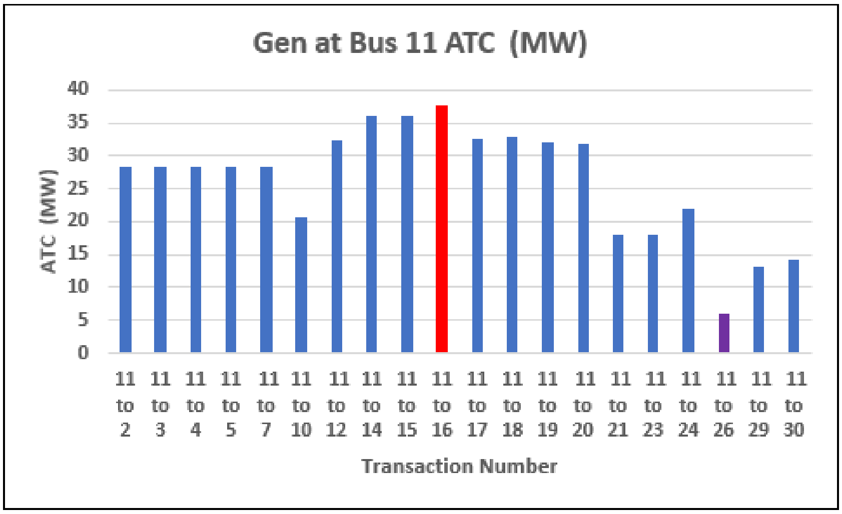

**Figure 4.11 Alteration in ATC for all transactions with Gen-11**

Figure 4.10 indicates the influence of the generator on ATC values when the injection is at bus no 8 on in the IEEE 30-Bus network. The line between buses 8 & 12 is having a maximum ATC of 70.41 MW and the line between buses 8 & 26 has a minimum ATC value of 12.18 MW. Further Figure 4.11 depicts the ATC distribution in different lines. When the generator is placed at bus number 11. The graph shows the maximum ATC in the line between buses 11 & 16 which equals 37.77 MW while the least ATC (6.09 MW) is in the line between buses 11 & 26.

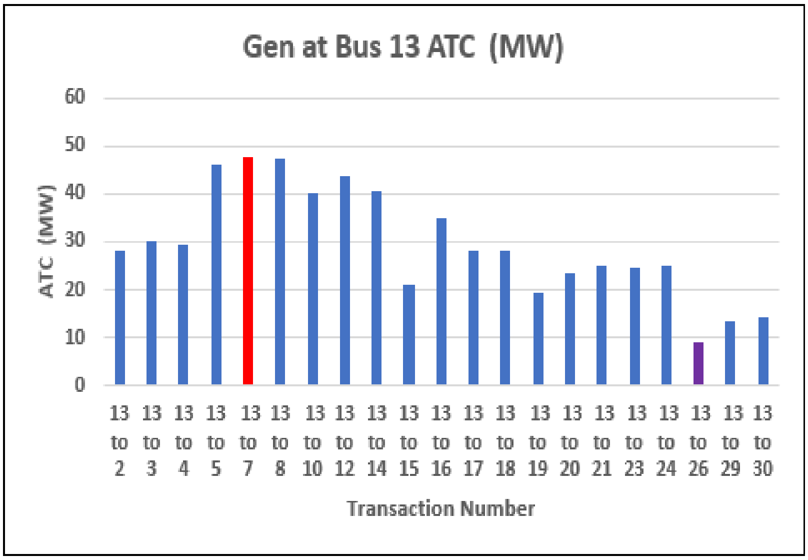

**Figure 4.12 Alteration in ATC for all transaction with Gen-13**

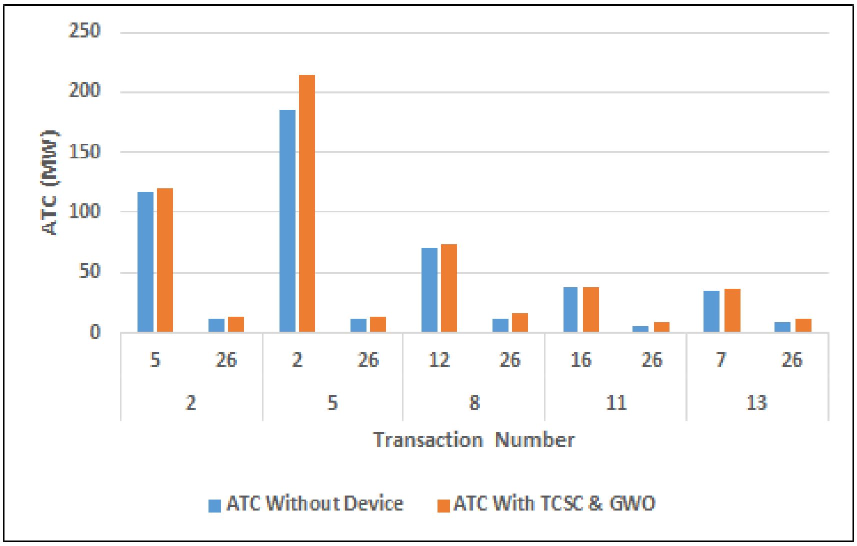

**Figure 4.13 ATC values without TCSC and with TCSC- GWO**

ATC distribution due to the generator at bus no 13 in the system considered is shown in Figure 4.12. Maximum ATC (34.67 MW) is obtained between buses 13-7 whereas the least value of ATC (8.89 MW) can be observed between buses 13-26. From Figure 4.8 to Figure 4.12 it can be witnessed that the value of ATC is maximum when the generator is connected to a near bus which is the seller bus as compared to the minimum value obtained when the generator is far by the buyer bus. ATC values without TCSC and with TCSC- GWO are depicted in Figure 4.13.

### Case I: Maximization of ATC

**Table 4.2 Consolidated results for ATC maximization**

| Bus | | OPF WITHOUT TCSC | | | OPF WITH TCSC | | |
|---|---|---|---|---|---|---|---|
| **SB** | **BB** | **ATC (MW)** | **TPL (MW)** | **TQL (MVAr)** | **ATC (MW)** | **TPL (MW)** | **TQL (MVAr)** |
| **2** | **5** | 116.65 | 7.01 | 30.5 | 120.75 | 7.13 | 28.33 |
| | **26** | 12.18 | 7.01 | 30.3 | 13.18 | 7.13 | 28.15 |
| | **2** | 184.56 | 7.03 | 30.1 | 215.13 | 7.45 | 29.78 |

|  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|
| **5** | **26** | 12.26 | 7.09 | 30.7 | 13.45 | 7.19 | 28.48 |
| **8** | **12** | 70.41 | 7.04 | 30.4 | 74.046 | 7.17 | 28.26 |
|  | **26** | 12.18 | 7.08 | 30.8 | 16.57 | 7.21 | 28.52 |
| **11** | **16** | 37.77 | 7.11 | 30.6 | 38.08 | 7.24 | 28.39 |
|  | **26** | 6.09 | 7.01 | 31.3 | 8.01 | 7.78 | 29.24 |
| **13** | **7** | 34.67 | 7.05 | 29.6 | 36.89 | 7.69 | 27.56 |
|  | **26** | 8.89 | 7.08 | 30.5 | 11.46 | 7.97 | 28.95 |

Table 4.2 shows the results when the program runs for the objective of maximizing ATC between the buses under transaction with GWO. Figure 4.12 depicts that with the help of GWO ATC values attained between bus 2-26, 5-26, 8-26, 11-26 & 13-26 are 12.18 MW, 12.26 MW, 12.18 MW, 6.09 MW & 8.89 MW respectively which shows upper hand over the results obtained with Firefly algorithm [104]. TCSC when optimized for location and parameter setting with GWO gives improved results when compared to other FACTS devices.

Different ATC values (both maximum and minimum) are calculated and are again utilized in OPF for further enhancement. GWO is applied on the IEEE 30-Bus system for enhancing ATC by optimally placing and sizing TCSC. Table 4.2 shows the output of ATC maximization with the TCSC implemented. Firstly, OPF is applied and then TCSC is implemented for further calculations. The results are graphically represented in Figure 4.14. In table 4.2 SB represents the seller bus and BB denotes the buyer bus. TPL denotes total real power loss while TQL represents a net loss of reactive power of the system. ATC maximization is done by optimally searching the location of TCSC.

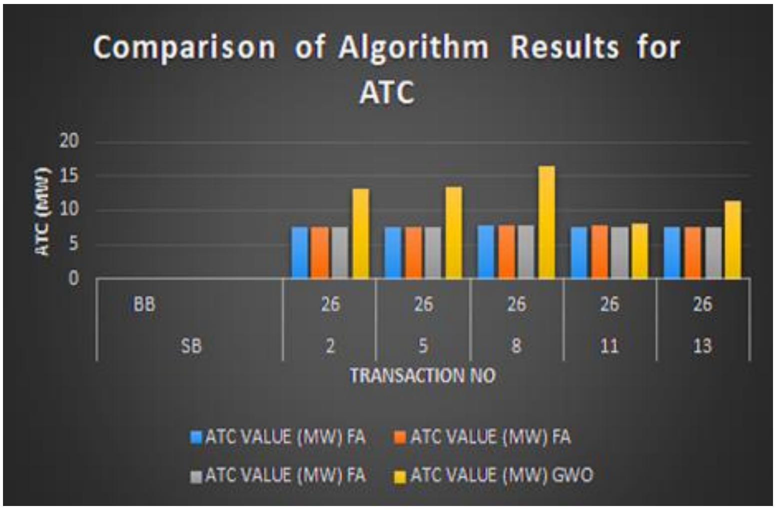

**Figure 4.14 Comparison of ATC results with Firefly Algorithm [120] and TCSC- GWO**

The exploration algorithm proficiently located the device for maximizing the objective function under consideration. With explicit distribution and sizing of TCSC by applying GWO, net reactive power loss is reduced when compared with the base case. Total active power losses increase with the increase in ATC value as enhanced power is transacted through lines. When compared with other EP, the percentage of ATC enhancement with GWO is much more significant. The ATC value between far-away buses and generator buses is enhanced as compared to that calculated with other EP. ATC value is increased by 8.2% in the transaction between 2 – 26 from 12.18MW to 13.18MW.

When transaction with far away bus i.e., between 5-26, 8-26, 11-26, and 13-26 is considered ATC value is enhanced by 9.7%, 36.04%, 31%. and 29% respectively. These ATC value enhancements in magnitude are more significant than those attained by applying FA [113].

### Case II: Minimization of Total Active Power Loss

**Table 4.3 Consolidated results for PL minimization**

| Bus | | Load Flow OPF | | | Load Flow OPF-TCSC | | |
|---|---|---|---|---|---|---|---|
| SB | BB | ATC (MW) | TPL (MW) | TQL (MVAr) | ATC (MW) | TPL (MW) | TQL (MVAr) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **2** | **5** | 116.6 | 7.01 | 30.0 | 90.67 | 5.06 | 28.56 |
| | **26** | 12.18 | 7.01 | 30.3 | 8.34 | 5.61 | 29.23 |
| **5** | **2** | 184.56 | 7.03 | 30.1 | 165.67 | 5.89 | 29.67 |
| | **26** | 12.26 | 7.09 | 30.7 | 9.45 | 5.63 | 31.67 |
| **8** | **12** | 70.41 | 7.04 | 30.4 | 45.89 | 5.32 | 26.89 |
| | **26** | 12.18 | 7.08 | 30.8 | 7.54 | 5.12 | 24.78 |
| **11** | **16** | 37.77 | 7.11 | 30.6 | 32.78 | 5.32 | 32.78 |
| | **26** | 6.09 | 7.01 | 31.3 | 6.03 | 4.32 | 45.89 |
| **13** | **7** | 34.67 | 7.05 | 29.6 | 32.43 | 5.67 | 27.54 |
| | **26** | 8.89 | 7.08 | 30.5 | 9.54 | 6.03 | 31.67 |

The consolidated results for the objective to reduce active power loss have been shown in Table 4.3 where active power losses are reduced when compared to that obtained while ATC maximization is done.

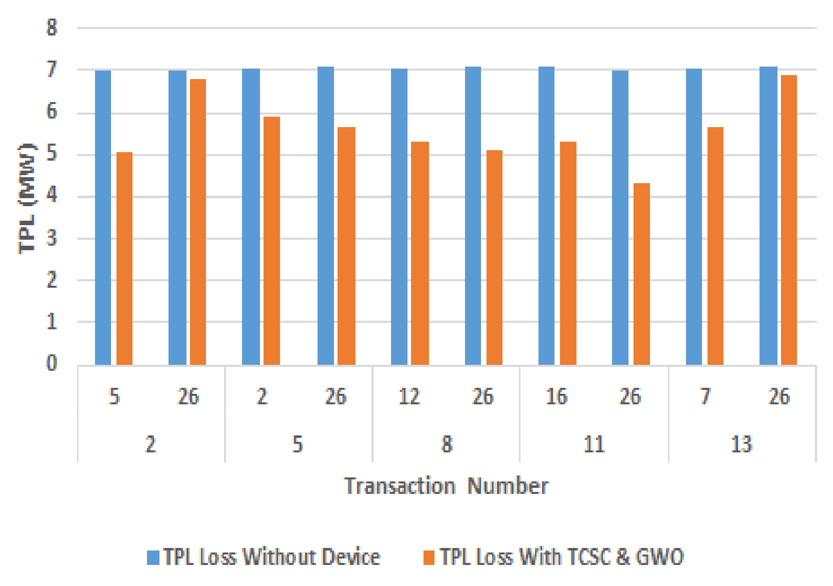

**Figure 4.15 TPL values with and without TCSC**

Here ATC value is reduced due to a reduction in active power losses. It can also be observed that in this case also reactive power loss is reduced due to the optimized TCSC location. Figure 4.15 shows the variation of Active power loss with and without TCSC GWO. Comparative results for TPL reduction while GWO optimized TCSC is implemented in the system are represented in Figure 4.18. It can be well established that the percentage reduction of TPL when considering OPF with and without TCSC using GWO is higher in most of the transactions.

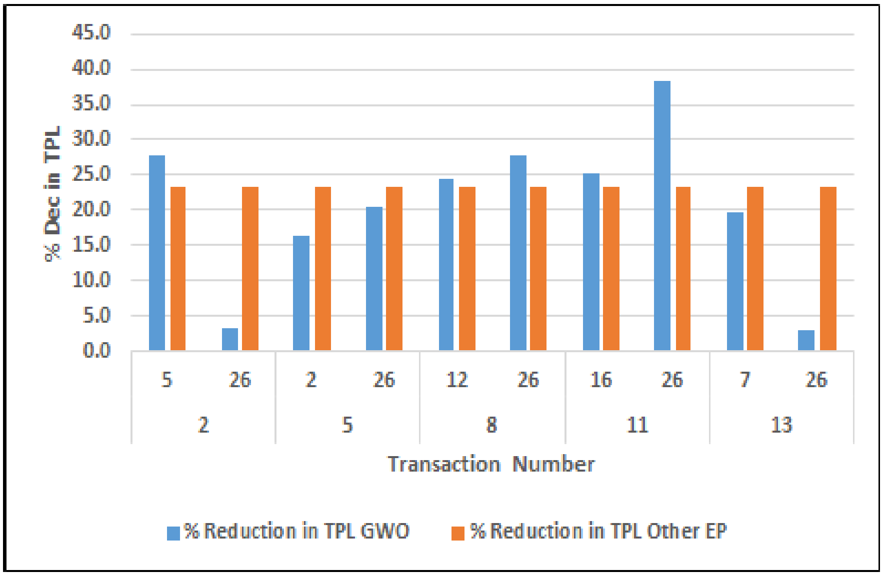

**Figure 4.16 comparison of % Decrement in TPL**

**Table 4.4 Location and parameter setting of TCSC by GWO**

| SB | BB | For ATC Maximization | | For TPL Minimization | |
|---|---|---|---|---|---|
| | | TCSC Loc | TCSC Size | TCSC Loc | TCSC Size |
| 2 | 5 | 12 | -0.6977 | 6 | -0.6024 |
| | 26 | 19 | 0.2676 | 9 | 0.3052 |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| 5 | 2 | 2 | 0.1091 | 35 | 0.2677 |
|  | 26 | 8 | -0.576 | 17 | 0.4912 |
| 8 | 12 | 16 | -0.0724 | 21 | -0.1838 |
|  | 26 | 38 | -0.3927 | 36 | -0.5804 |
| 11 | 16 | 6 | 0.3439 | 6 | 0.6197 |
|  | 26 | 19 | 0.6907 | 38 | 0.3093 |
| 13 | 7 | 26 | -0.6112 | 26 | -0.2724 |
|  | 26 | 5 | 0.2479 | 5 | 0.3052 |

Table 4.4 illustrates the optimized parameter and location of TCSC with the application of GWO.

## CONCLUSION

A multi-objective function including ATC enhancement and total power loss reduction is being achieved here by implementing the series FACTS device, TCSC. The site of TCSC placement is decided by applying ACPTDF as the sensitivity factor while the parameter is optimized with the help of the GWO algorithm. These two conflicting objectives are effectively treated and while enhancing ATC the power losses are also increased but are reduced by about 15% as compared to that enhanced without TCSC implementation. Moreover, the reduction in ATC value while reducing power losses is 10% less as compared to that reduced without TCSC. Here, the location of TCSC with ACPTDF and optimization of parameter setting with GWO has increased the ATC effectively with a decrease in the increment of power losses with it. Also, the ATC is enhanced for the line connected between far away buses which is a significant result obtained out of the multi-objective function.

# CHAPTER V

# HYBRID PSO-GWO OPTIMIZED FACTS FOR MITIGATING CONGESTION USING SENSITIVITY FACTORS

## 5.1 INTRODUCTION

Transmission congestion is one of the menaces that power systems now a day is facing. The growing competition in deregulated power markets market has elevated the load on present transmission lines. This escalated stress on the lines and equipment has challenged the system to work securely and efficiently. The lines are working on or beyond the safety thermal limits triggering congestion in the system [115]. During congestion, the system not only becomes highly unreliable and insecure but it increases power charges which led to load cutting on the consumer end making system uneconomical. This condition must be treated with preference to limit price hikes as well as dropping out of loads. FACTS devices can play an influential role in reducing the overloads on lines and alleviating congestion. These devices can be voltage source converter based or there may be variable impedance-based. FACTS works most effectively when optimized for exact location and parameter setting [123].

In literature, numerous methods and heuristic/metaheuristic schemes have been proposed to search for the optimal location and size of FACTS. With the increasing demand for reactive power in the system, the voltage profile gets deteriorated hence integrating static VAR in the system for reducing power losses and improving the voltage profile of the system, Immune Algorithm and Guaranteed convergence Particle swarm Optimization (GPSO) have been proposed [124]. UPFC has been implemented to reduce or eliminate the overloaded lines to reduce system losses and reduce voltage deviation. The location and parameter setting are optimized by the Differential Algorithm (DA) and GA in the N-1 contingency condition to improve system security. The results are validated on IEEE 6 bus and IEEE 14 bus systems [125].

Shunt FACTS devices play a major role in reducing reactive power losses. Another FACTS device, SVC has been optimized and tuned for its location and parameter setting applying GA, PSO, and hybrid GA-PSO. The applied hybrid GA-PSO algorithm reduced system reactive power loss and enhanced the stability of the power system [126]. ATC enhancement is a crucial method to mitigate congestion. By increasing ATC, the loadability of the line can be increased hence the lines will not be overloaded and can operate under safe thermal constraints. TCSC and SVC have been implemented by application of real coded GA to enhance the ATC of the system [127]. Effective voltage deviation and system loss reduction by implementing TCSC have been reported using ABC and PSO [128]. A Brainstorm optimization algorithm was proposed in [10] for optimal location and parameter setting of SVC and TCSC so as to improve voltage profile and reduce losses [129].

Applying sensitivity factors is one of the effective methods for searching for the optimal location of FACTS devices. The sensitivity factor calculated as the ratio of change in loading factor with respect to change in reactive power generation has been applied to locate UPFC, TCSC, and SVC to reduce active power overloads and to increase voltage [130]. FACTS devices are costly if the location and size are not optimized. For reducing the cost of TCSC together with the reduction in generation cost, the authors proposed the real power flow PI sensitivity factors for allocating TCSC and PSO-TVAC be applied to reduce the generation cost & capital cost of TCSC [131].

Power transfer distribution factors (PTDF) which is an AC sensitivity factor have been used to enhance ATC by optimal placement of SSSC, STATCOM, and UPFC [132]. Voltage stability margin (VSM) and corrected transient stability margin (CTEM) have been proposed to determine the most congested line and then allocate TCSC for managing congestion [133]. Further optimized location of TCSC and STATCOM has been determined by reactive power loss sensitivity indices which were suggested with respect to the controlling parameters of the devices for mitigating congestion [134]. Line voltage stability Index (LVSI) was employed for augmenting the location of TCSC to increase power system voltage stability and reduce congestion [135]. A loss sensitivity index has been calculated by applying the reactive power loss reduction approach together with stability indices have been applied for searching for the optimal location of TCSC to minimize congestion [136]. A new sensitivity factor, the Disparity line utilization factor (DLUF) has been proposed for determining the appropriate location of IPFC, and GSA was used for tuning IPFC to ease congestion [137].

As per the literature survey, TCSC is found to be a versatile device that is cost-effective and simple to implement. Its property to swiftly regulate the reactance of the line in which it is connected is very useful in direct control of the power flowing through it. When the power system is mathematically modeled it results in a very non-linear and complicated set of equations. Thus, heuristic methods are to be applied to get the most nearby solution to the problem formulated.

Mathematical modeling displays the exceedingly non-linear nature of the power system. These non-linear equations cannot be solved by traditional mathematical methods. To solve the objectives considered the algorithms discussed earlier in the chapter are to be employed. This chapter presents the congestion mitigation in power systems using a novel method of hybridization of the GWO algorithm [104] with PSO. The efficiency of GWO of definite convergence is due to its efficient exploration property, while efficient exploitation is the property of PSO. Here the problem is initialized through GWO and further converged through PSO. This HPSOGWO is uniquely applied to the objective and congestion is minimized to significant values. TCSC is used as a FACTS device for mitigating congestion. The heavily congested line is obtained by the Line utilization factor (LUF) as the sensitivity factor. DLUF is a very useful sensitivity index used to determine the most appropriate location of TCSC. The optimal size of TCSC is calculated by HPSOGWO by solving a multi-objective function involving a reduction in voltage deviation, active power losses, and improvement of security margin. The proposed algorithm is tested on a standard IEEE 30-Bus system for defined contingency conditions. A comparison of results obtained with HPSOGWO is presented with those obtained by GWO and PSO when applied individually.

## 5.2 APPLIED SENSITIVITY INDICES

For getting desired results from FACTS devices in the congested network, these must be suitably placed and optimized for their parameters. If not placed at a suitable location then this makes the system uneconomical as will not perform the function to optimize power system work under congested conditions. The system analysis with FACTS when done with the help of sensitivity indices instead of other research and analytical methods, the results obtained are more effective and economic for reducing system congestion [138],[139]. This chapter implements, the Disparity line Utilization Factor (LUF) which is an effective sensitivity index, to attain the optimal placement of the FACTS device.

LUF helps to calculate the extent of loading of a transmission line and it is defined as the ratio of MVA flowing in the line between buses $i$ and $j$ to the rated capacity MVA flow of the line. A higher value of LUF indicates that the line is congested. Analytically, LUF can be represented as:

$$LUF_{ij} = \frac{MVA\ flow\ in\ Line_{ij}}{Max\ capacity\ of\ MVA\ flow\ in\ Line_{ij}} \tag{5.1}$$

With equation (5.1) LUF of different lines is calculated and then the results are sorted for the most congested line. The loading on this congested line has to be reduced by optimally placing TCSC. For getting the optimal location, DLUF for the lines connected to the most congested line is calculated. TCSC is located in the line which has the smallest value of DLUF and it can be calculated as:

$$DLUF_{(ij-il)} = \left|LUF_{ij} - LUF_{il}\right| \tag{5.2}$$

Where,

$LUF_{ij}$- LUF of most congested line

$LUF_{il}$- LUF of line connected to most congested line

$DLUF_{(ij-il)}$- is DLUF of line pair *ij* & *il* connected to a common bus *i*.

## 5.3 APPLIED MODEL OF TCSC

The applied model of TCSC is presented in Figure 5.1 represents the model of TCSC for regulation of the reactance to modify the power flowing through the line.

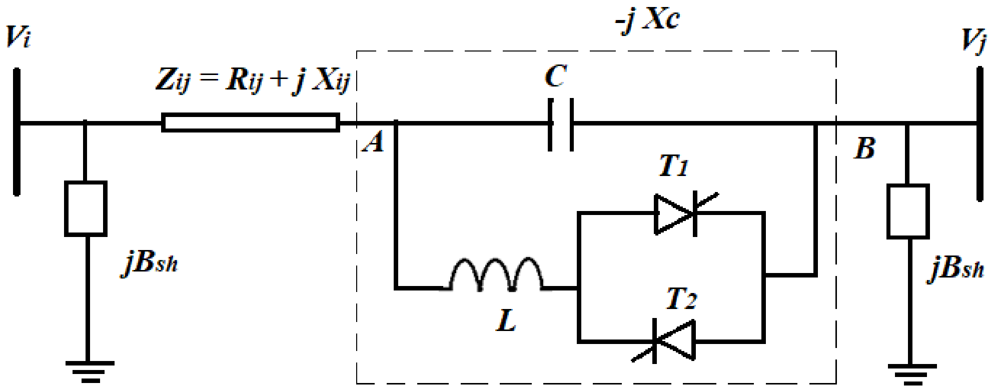

**Figure 5.1. TCSC in the transmission line between bus *ij***

This is realized when TCSC either works in adjustable capacitive mode or variable inductive mode as shown in Figures 5.2 (a) & 5.2(b).

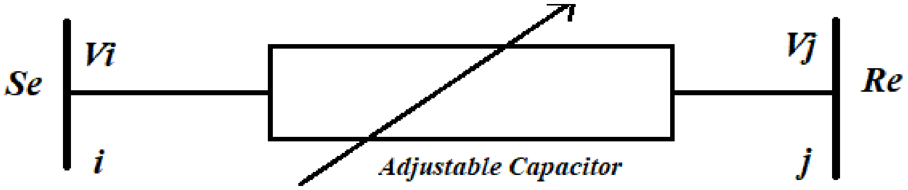

**Figure 5.2(a) Adjustable Capacitive TCSC model**

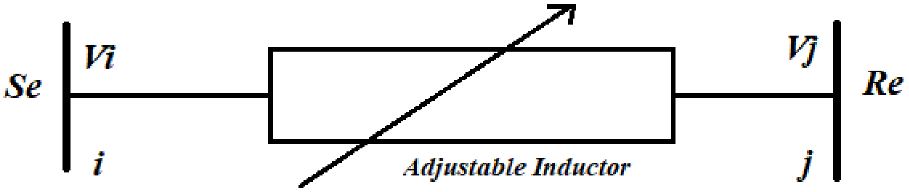

**Figure.5.2(b) Adjustable Inductive TCSC model**

Current injected at $i_{th}$ bus can be written as:

$$I_i = V_i \times Y_{ij} \tag{5.3}$$

and corresponding admittance as:

$$Y_{ij} = G_{ij} + jB_{ij} \tag{5.4}$$

Where, $G_{ij}$ & $B_{ij}$ represents conductance and susceptance of line *ij* respectively.

The impedance of TCSC can be calculated as:

$$Z_{AB} = \frac{V_{AB}}{I_L} \tag{5.5}$$

With the change in TCSC impedance, $Z_{AB}$ will change the line admittance as given by equation (5.6)

$$\varDelta Y_{RS} = y'_{RS} - y_{RS} \tag{5.6}$$

So,

$$\varDelta Y_{RS} = (G'_{RS} + B'_{RS}) - (G_{RS} + B_{RS}) \tag{5.7}$$

Where,

$$G_{RS} = \frac{R_{RS}}{\sqrt{R_{RS}^2 + X_{RS}^2}} \quad \& \quad B_{RS} = \frac{-X_{RS}}{\sqrt{R_{RS}^2 + X_{RS}^2}} \tag{5.8}$$

$$G'_{RS} = \frac{R_{RS}}{\sqrt{R_{RS}^2 + (X_{RS} + X_{TCSC})^2}} \tag{5.9}$$

$$B'_{RS} = \frac{-(X_{RS} + X_{TCSC})}{\sqrt{R_{RS}^2 + (X_{RS} + X_{TCSC})^2}} \tag{5.10}$$

With the change in the value of TCSC reactance, $X_{AB}$ manipulates the value of bus admittance, $Y_{AB}$ which in turn alters the elements of the Jacobian matrix of the system. The changed values of admittance are then applied in load flow analysis to get variation in the line flows.

## 5.4 OBJECTIVE FUNCTION

The congestion mitigation problem can be formulated in terms of the multi-objective function and can be presented as in equation (5.11):

$$f = h_1 \times SM + h_2 \times P_L + h_3 \times VD + h_4 \times X_{TCSC} \qquad (5.11)$$

The value of weight factors $h_1$ , $h_2$ , $h_3$ & $h_4$ are programmed to 0.25.

**(a)** SM in equation (11) is a security margin which can be mathematically represented as:

$$SM = \frac{\sum S_A - \sum S_R}{\sum S_A} \qquad (5.12)$$

Where,

$S_A$- Actual power flow in all the lines connected to load buses in MVA
$S_R$- Rated power flow in all the lines connected to load buses in MVA
The value of SM must lie between 0 & 1, for the normal operation of the power system. Thus, for minimizing the objective function in equation (5.11), equation (5.12) can be rewritten as:

$$1 - SM = \frac{\sum_{k\in\, kload} S_k in}{\sum_{k\in\, kload} S_k cons.} \qquad (5.13)$$

**(b)** Power loss $P_L$, can be given by equation (5.14):

$$P_L = \begin{pmatrix} |V_p^2| G_{pq} - |V_p||V_q|[G_{pq} \cos\theta_{pq} + B_{pq} \sin\theta_{pq}] \\ -|V_p||V_{snpq}|[G_{pq} \cos\theta_{snpq} + B_{pq} \sin\theta_{snpq}] \end{pmatrix}$$

$$+ \begin{pmatrix} |V_q^2| G_{pq} - |V_p||V_q|[G_{pq} \cos\theta_{pq} + B_{pq} \sin\theta_{pq}] \\ -|V_q||V_{snpq}|[G_{pq} \cos\theta_{snpq} + B_{pq} \sin\theta_{snpq}] \end{pmatrix}$$

(5.14)

**(c)** Equation (15) describes the Voltage deviation:

$$VD = \sum_n^{NB} |V_n - V_r|^2 \qquad (5.15)$$

$V_n$ & $V_r$ are the actual and optimal values of voltage at bus *n* respectively

**(d)** TCSC reactance, $X_{TCSC}$:

In this paper the value of TCSC reactance is limited to:

$$-0.8X_L \leq X_{TCSC} \leq 0.2X_L \tag{5.16}$$

## 5.5 CONSTRAINTS

**Table 5.1 Constraints applied to the System**

| S No. | Constraints | Equation |
|---|---|---|
| 1 | Active power balance | $P_{gi} - P_{di} - P_i(V_i, \theta_i) = 0$ |
| 2 | Reactive power balance | $Q_{gi} - Q_{di} - Q_i(V_i, \theta_i) = 0$ |
| 3 | Generated real power | $P_{gi}^{min} \leq P_{gi} \leq P_{gi}^{max}$ |
| 4 | Generated reactive power | $Q_{gi}^{min} \leq Q_{gi} \leq Q_{gi}^{max}$ |
| 5 | Bus voltage limits | $V_i^{min} \leq V_i \leq V_i^{max}$ |
| 6 | TCSC reactance | $X_{tcsc}^{min} \leq X_{tcsc} \leq X_{tcsc}^{max}$ |

In Table 5.1,

$P_{gi}$ - Real power generated at $i_{th}$ bus

$Q_{gi}$ - Reactive power generated at $i_{th}$ bus,

$P_{di}$ - Real power demand at the $i_{th}$ bus

$Q_{di}$ - Reactive power demand at the $i_{th}$ bus

and $V_i$ & $\theta_i$ are the voltage and its analogous angle at $i_{th}$ bus.

## 5.6 OPTIMIZATION ALGORITHMS

### 5.6.1 Grey Wolf Optimizer

The Grey wolf optimizer is explained in the previous chapter in section 4.4. The pseudo-code can be given as below

```
Pseudocode -Grey Wolf optimization

Step1: set initial GWO variables (a, Â , Ĉ)

Step2: Set the number of grey wolves (n=100)
```

```
Step 3: initialize iteration count, iter =0
Step 4: Appraise fitness value ∀ wolves and apply to sort for best positions as α, β & γ.
Step 5: Evaluate ‘a’ from 2 to 0 as per the equation below:
        $a(iter) = 2 \times iter\ number \left(\frac{2}{\max iter}\right)$
Step6: Update coefficient vectors A & C and calculate the location of α, β & γ.
Step 7: Assess the location of each solution
Step 8: for the same position
 end,
else, update iter count to iter =iter+1and
 start again at Step 4.
```

### 5.6.2 Particle Swarm Optimizer

PSO is an iterative analytical method to compute the solution of non-linear mathematical problems of the power system (here). Here an initial population of moving particles is anticipated which moves in a defined search space to get the solution to the formulated mathematical problem of the power system under consideration. Individual particle’s velocity, as well as its local best position, is found by obtaining the best positions in search space [133].

*Pseudocode for Particle Swarm Optimization*

```
Step 1: Initialize :
       for  particle  population in Space
          for  the search dimension d in D
     set iteration counter, iter =0
Step 2: Initialize
```

```
            particle  position (arbitrarily)
            $m(i,d)= arb (m_{min} , m_{max})$
            velocity arbitrarily in assumed dimension
            $v(i,d)= arb (v_{imin} , v_{imax})$
            end for
            particle i,  best position $P_{bi} =m_i$
    Step3 : update global best position of i :
                if  $P_{bi} < G_b$
            Then substitute $G_b=P_{bi}$
              end if
        end for
    Step 4: Update each particle's best position in S
             if  $m_i < P_{bi}$, then substitute $P_{bi} = m_i$
             end if
            if  $P_{bi} = G_b$, then substitute $G_b = P_{bi}$
            end if
    Step 5: Update for particle's velocity
            $v_{(i,d)} = v_{(i,d)} + C_1 * rnd(0,1) * \{P_{b(i,d)} - m_{(i,d)}\} + C_1 * rnd(0,1) * \{G_{bd} - m_{(i,d)}\}$
             and its position
                $m_{(i,d)} = m_{(i,d)} + v_{(i,d)}$
    Step6: increment iteration, itr=itr+1, till itr=itr_max
```

### 5.6.3 HPSOGWO

In HPSOGWO, the method to find the solution is changed. The algorithm is initialized with PSO. Here the best location of particles is sorted and to elude the problem of local minima an error, $e = \{0, 1\}$, is introduced in the algorithm. The reason to introduce the error is to avoid the premature convergence of the algorithm at local minima. The best position of a particle is obtained from PSO. This position of the particle is considered the initial position of Grey Wolfs. Now the GWO algorithm is carried out to find the best fitness value of the solution in the form of the best location. These positions are now considered the new updated positions of particles in PSO.

*Pseudocode Hybrid GWO- PSO (HPSOGWO)*

```
1.  Arbitrarily generate initial population
2.  Set prob.= slight probability degree
3.  Define the maximum iteration number
4.  Run PSO to calculate the fitness of every
    particle.
5.  Sort for the best fitness values of
    particles
6.  if iteration =$iter_{max}$ ,  stop
            else, apprise the velocity and
    position of the particle
7.  For current particle
        if rand(0,1) < prob , then establish
            the values a, A & C (for evading
            local minima)
        else, go to step 4
8.  From 7 evaluate the fitness of all wolves
9.  Update the position vectors $X_a$, $X_b$ & $X_c$
10. if the number of iteration is less,
            calculate the average position of
            the three best wolves , substitute
            it with the existing particle & go
            to step 4
```

```
    else, acquaint the position of grey wolves
11. Update the value of a, A & C and go to step 7
```

## 5.7 RESULT ANALYSIS AND DISCUSSION

For validation of the proposed algorithm on the IEEE 30-Bus system, four different cases are considered as shown below:

1. Base case with ordinary operational environment of the system being considered.
2. N-1 contingency: outage line number 12.
3. 150% overloading of the system
4. 180% overloading of the system.

In all the above cases HPSOGWO has been applied and the results hence obtained are compared with those obtained by applying PSO and GWO individually. The results are obtained for reduction of real power loss, bus voltage deviation, enhanced security margin, and efficient redistribution of LUF in the congested lines.

### 5.7.1 LUF REDISTRIBUTION

**Case 1: Normal Operating condition**

The calculated LUF values for all the lines with no TCSC & TCSC located by the application of PSO, GWO, and HPSOGWO are shown in Figure 3. Then DLUF is calculated for finding the optimal location of TCSC.

From Figure 5.3 it can be seen that with LUF 0.699, line 18 between bus 12 and bus 15 is the most congested line. This line number 18 is connected to:

- Line number 16 between bus 12 and bus 13
- Line 17(bus 12-14) and
- Line19 (bus 12-16).

DLUF values are to be evaluated for lines 16, 17, and 19 with respect to line number 18 for optimal placement of TCSC. The minimum value of DLUF indicates the best location of TCSC. Table 5.2 illustrates DLUF values calculated for lines 16,17 and 19 with respect to line 18.

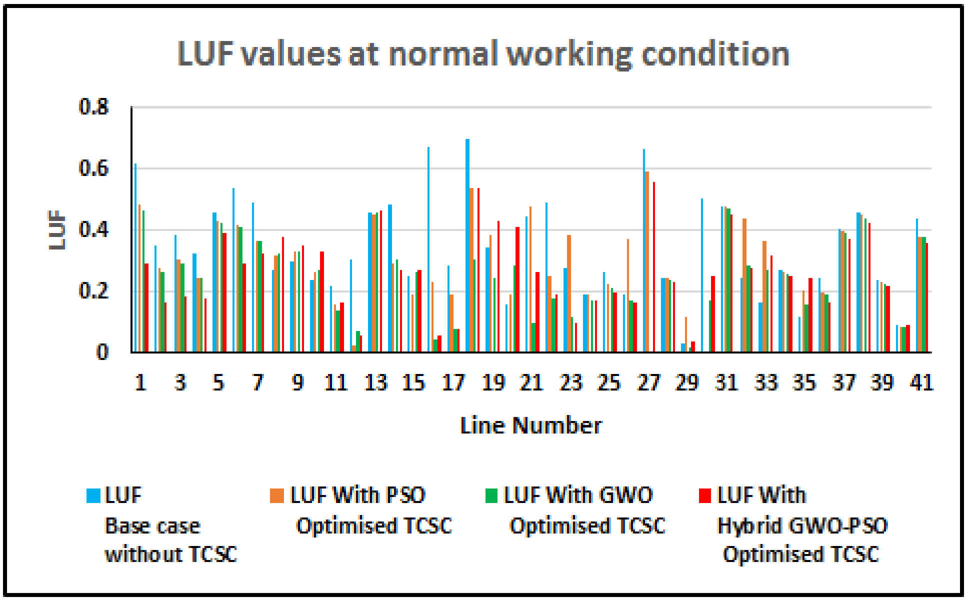

**Figure 5.3 LUF values with no TCSC, & with GWO, PSO, and HPSOGWO tuned TCSC for normal conditions**

**Table 5.2 Combined DLUF values for the normal operating conditions**

| SB | RB | DLUF |
|---|---|---|
| 12 | 13 | 0.028 (min) |
| 12 | 14 | 0.424 |
| 12 | 16 | 0.36 |

From Table 5.2, it can be observed that the minimum value of DLUF is obtained at line no 16, with bus 12 as SB and bus 13 as BB. Thus TCSC is to be connected at line number 16 as it is the optimized location calculated by DLUF for mitigating congestion. Now to attain the objectives formulated in equation (11), TCSC has to be tuned for its reactance value. This parameter setting is done by applying GWO, PSO, and HPSOGWO.

Figure 5.3 also depicts that when TCSC is optimized by PSO in the base case the LUF of line 1 reduces from 0.62 to 0.49Hence relieving the congestion. The LUF value is further decreased to 0.461 when the location of TCSC is optimized with GWO. Now when HPSOGWO optimizes TCSC location the LUF value is decreased to 0.287 which is the lowermost of all. Thus, LUF redistribution is best achieved in the case of HPSOGWO, clearly most effective to mitigate congestion. Further LUF of all the lines is demonstrated in Figure 5.3. It can be seen that some of the lines which were previously lightly loaded are now loaded appropriately. This can be seen in the case of lines number 8, 9, and 10. Line 8 which previously had LUF as 0.266, is now reloaded with LUF as 0.322 when optimized by GWO, with LUF as 0.317 when TCSC optimized by PSO, and 0.375 when HPSOGWO is applied. The same pattern of LUF redistribution can be seen for lines number 9 and 10 when TCSC connected is optimized by GWO, PSO, and HPSOGWO. The results of LUF are shown for other lines also. The LUF value of congested lines is reduced hence reducing congestion after optimizing TCSC location by PSO, GWO, and HPSOGWO. Also, the lines with low values of LUF such as 8, 9 & 10 are reloaded appropriately. Previously lightly loaded line 8 with LUF 0.266 is reloaded to increase the LUF to 0.322 applying GWO, 0.317 applying PSO, and 0.375 by applying HPSOGWO. On the contrary, similar redistribution of LUF can be seen in lines 9 & 10.

**Case 2: Outage of Line no 12**

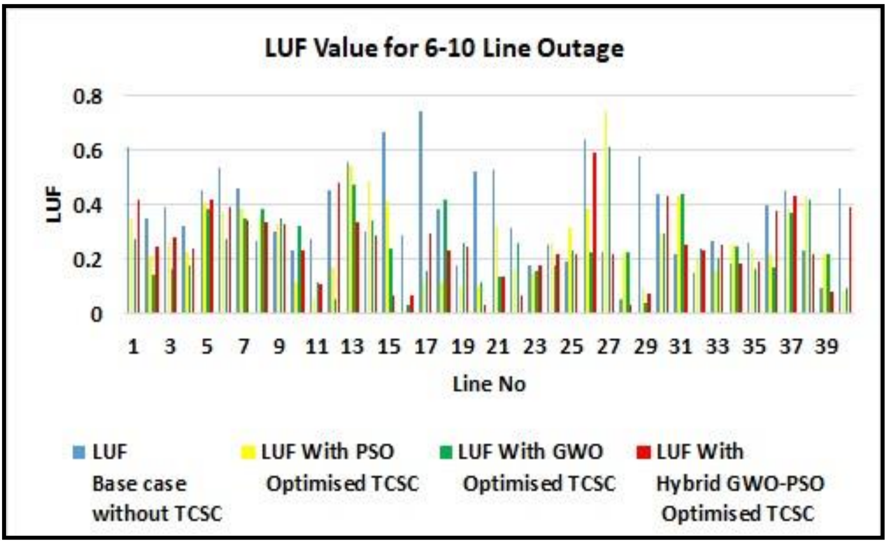

**Figure 5.4 Values of LUF for an outage of line number 12 without TCSC & using PSO, GWO and HPSOGWO optimized TCSC**

TCSC is then placed with calculated values of DLUF. Line number 18, between sender bus12 and buyer bus 15 becomes congested due to an outage of line number 12, with the maximum LUF value increased to 0.745. This overloads the line. Here line 16, line 17, and line19 are connected to bus 12. Hence, DLUF is to be evaluated for lines 16,17, and 19 with respect to line 18. The minimum value of DLUF is obtained for line number 16 which is the optimal location of TCSC. Figure 5.4 shows the LUF values obtained without and with TCSC optimized for parameters with GWO, PSO, and HPSOGWO Table 5.3 demonstrates the values of DLUF calculated for lines number16, line number 17, and line number 19 with respect to line 18.

**Table 5.3 Combined values of DLUF outage of line number 12**

| SB | RB | DLUF |
|---|---|---|
| 12 | 13 | 0.076(min) |
| 12 | 14 | 0.454 |
| 12 | 16 | 0.364 |

**Case -3: Overloading of the system by 150%**

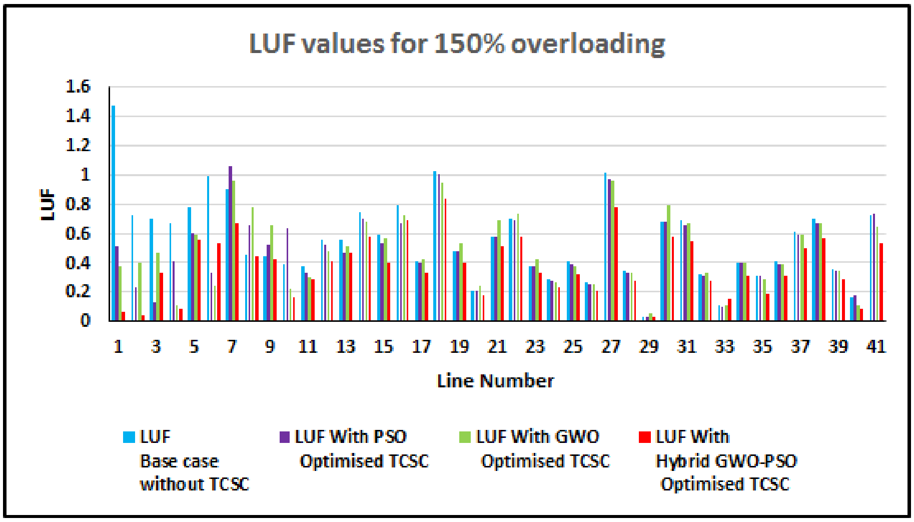

**Figure 5.5 LUF for 150% system overloading without TCSC and with PSO, GWO, and HPSOGWO optimized TCSC**

LUF values for all lines with no TCSC and PSO, GWO, and HPSOGWO tuned TCSC are calculated and are demonstrated in Figure 5.5. It can be observed that line number 1 is the most congested. Also, line number 2 is in connection with bus 1. So here DLUF is evaluated with respect to line number 1,. So, the optimal location of TCSC will be line number 2. When the system is overloaded by 150% the LUF value for line 1 increases to a high of 1.47 without TCSC. Now when TCSC is optimized with PSO LUF value is reduced to 1.06 which is still the reading for the congested line. GWO optimized TCSC reduces LUF to 0.957. When HPSOGWO optimizes TCSC the LUF value decreases to 0.866 which is considerably less and the line is relieved from congestion

**Table 5.4 Consolidated values of DLUF for the line coupled to bus 1with respect to line 1-2**

| SB | RB | DLUF |
|---|---|---|
| 1 | 3 | 0.739 |

### Case-4: Overloading of the system by 180%

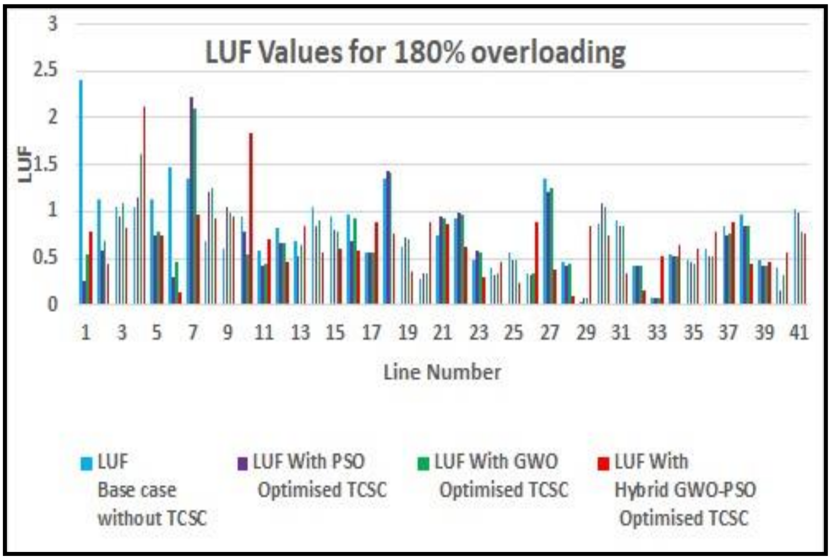

**Figure 5.6 LUF for 180% system overloading without TCSC and with PSO, GWO, and HPSOGWO optimized TCSC**

Figure 5.6 shows calculated values of LUF without TCSC & then with TCSC located optimally and tuned using GWO, PSO, and HPSOGWO. Here also line 1(bus 1-2) is heavily overloaded. Line 2 is also connected to the common bus 1. Therefore, the DLUF is evaluated for line 2 with respect to line number 1.

Hence here also, line number 2 is the optimal location of TCSC. The LUF of line 1 reaches 2.41 as the system is overloaded by 180% and hence becomes highly congested. PSO optimized TCSC reduces the LUF value to 2.22 and when the TCSC parameter is optimized and located at a suitable location by GWO the value of LUF reduces to 2.12. On the other end when TCSC is optimized with HPSOGWO, the maximum LUF value is significantly reduced to 0.940.

**Table 5.5 DLUF of the lines with 180% overloading**

| SB | RB | DLUF |
|---|---|---|
| 1 | 3 | 1.28 |

Based on the above four cases the values of different objectives of the multi-objective function in equation (10), are calculated.

## 5.8 ACTIVE POWER LOSS REDUCTION

Figure 5.7 displays the calculated active power loss for all four cases i.e. normal loading, line outage, 150% overloading, and 180% overloading:

### 5.8.1 Normal Operating Condition

TCSC is firstly positioned and optimized for the reactance parameter and then the OPF is carried out. TCSC optimized to -0.305 p.u. and located at line 16 between bus 12-13 using GWO, it is optimized to -0.13p.u. by applying PSO and is adjusted to -0.456p.u. with the use of HPSOGWO.

Figure 5.7 shows that in normal operating conditions real power loss is decreased to 4.50 MW from 6.85MW while applying PSO. With the application of GWO active power loss is further decreased to 3.92 MW.

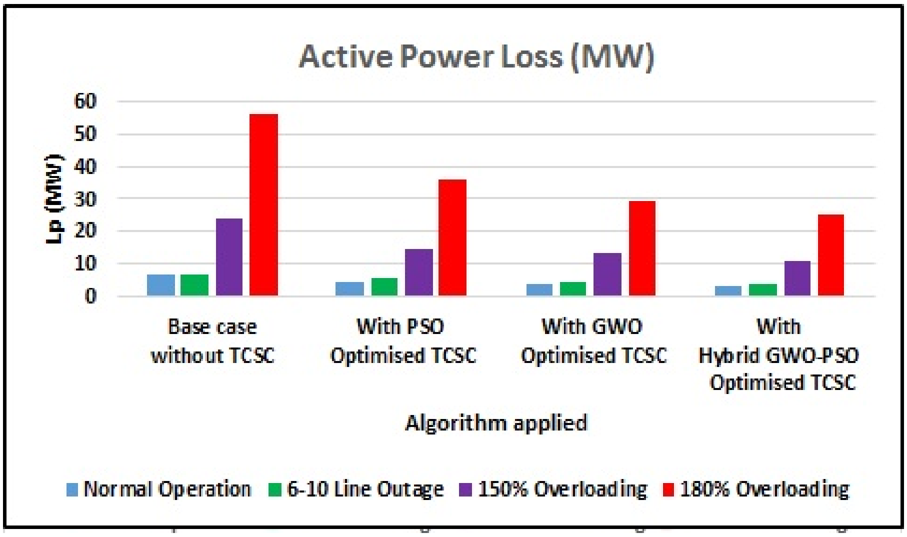

**Figure 5.7 Comparative display of reduction in power loss (MW) without TCSC and with TCSC**

TCSC when optimized with HPSOGWO the active power loss is 3.05 MW, this reduction is markedly low in comparison with the other two methods.

### 5.8.2 Outage of Line Number 12

With outage of line 12, the TCSC is placed at line number 16 where DLUF has a minimum value and the reactance of TCSC is adjusted to -0.305p.u. with GWO, TCSC is located at line number 16 with reactance set to 0.191p.u.. by applying PSO and by using HPSOGWO the TCSC reactance is set to -0.526p.u.. From Figure 5.7 it can be understood that with PSO optimized TCSC active power loss is 5.75 MW, it is decreased from 6.93 MW to 4.20MW when GWO optimized TCSC is placed. With the use of HPSOGWO, active power loss is additionally reduced to 3.75 MW. In this case, also HPSOGWO optimized the TCSC parameter to decrease the active power loss by a noticeable amount.

### 5.8.3 Overloading of The System By 150%

While applying GWO, TCSC is located at line 2 (bus 1-3) after DLUF is calculated and the parameter is optimized to -0.584p.u.. Real power loss is decreased from a base case of 24 MW to 13.2 MW by using GWO. PSO optimizes the TCSC to a value -0.632p.u. with active power loss reduction to 14.3 MW. The reduction of active power loss reaches 10.7 MW with HPSOGWO optimized TCSC. The reactance of TCSC is optimized to -0.315p.u..This result signifies the efficiency of HPSOGWO over other methods.

### 5.8.4 Overloading of The System By 180%

The location of TCSC is found again at line number 2, with the help of the minimum value of DLUF. When TCSC is optimized with the help of PSO the TCSC value is found to be -0.356p.u. with a reduction of power loss to 36.1 MW from a base case of 56 MW. With TCSC optimized by GWO, the power loss was reduced to 29.2 MW with TCSC optimized to -0.583p.u.. When HPSOGWO OPF is carried out the TCSC is optimized to -0.687p.u. and the power loss is reduced to 25.2 MW.

## 5.9 VOLTAGE DEVIATION (VD) REDUCTION

For normal operation, Line number 12 outage and overloading by 150% and 180% the results are shown in Figure 5.8.

### 5.9.1 Normal Operating Condition

Figure 5.8 demonstrates the deviation in voltage profile while TCSC is optimized with GWO. VD is decreased from 0.0112p.u. to 0.00890 p.u. which is approximately 20.53%. When TCSC is optimized with PSO, VD is decreased from the normal case of 0.0114p.u. to 0.0100 p.u.. which amounts to approx. 10.07%. Again TCSC optimized with HPSOGWO reduces voltage deviation to 0.00829 p.u.. Here deviation is reduced approximately by 25.98%.

### 5.9.2 Outage of Line number 12

In the case of outage of line number 12, the voltage deviation is decreased from the base case of 0.0114p.u. to 0.00912p.u. with GWO optimized TCSC which is approximately 20%, while it is decreased from 0.0114p.u. to 0.0107p.u. with the implementation TCSC with PSO that is about 6.143%. Voltage deviation is decreased to 0.00523 p.u. by applying HPSOGWO to locate TCSC which is approximately 54%.

So results implicate that HPSOGWO gave improved results in comparison to GWO and PSO.

### 5.9.3 Overloading of the system by 150%

When the system is overloaded by 150%, the voltage deviation is reduced from the normal case of 0.035p.u. to 0.02p.u. with the application of GWO to optimize TCSC, it is reduced to 0.022 with PSO while changes to 0.02 again with the help of HPSOGWO. This is approximately 53%, 37%, and 50% respectively by applying GWO, PSO, and HPSOGWO for optimizing TCSC.

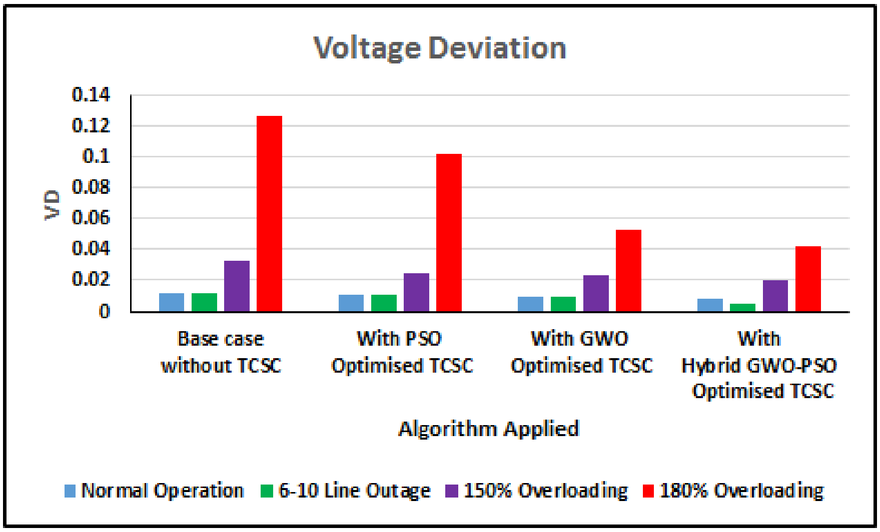

**Figure 5.8 Comparison of reduction in voltage deviation (p.u.) without TCSC and with GWO, PSO, and HPSOGWO optimized TCSC**

### 5.9.4 Overloading of The System By 180%

With the system overloaded by 180%, the voltage deviation reaches 0.126p.u. without TCSC. This increased VD is reduced to 0.0522 with the TCSC connected and parameter optimized by GWO, which amounts to approximately 58.04% reduction. With PSO optimized  TSCS the VD is decreased to 0.102p.u.. which is approximately 19.04%. TCSC now optimized with HPSOGWO decreases the VD to 0.0425p.u. which is 66%.

## 5.10 SECURITY MARGIN IMPROVEMENT

The effect of Line outage and overloading on system security margin is illustrated in Figure 5.9. The comparative analysis can be done from Figure 5.9 where the effect of line outage on

### 5.10.1 Normal Operating Condition

As shown in Figure 5.9, the security margin is enhanced i.e. the value 1-SM is improved from 0.945 to a lower value of 0.925 when GWO is applied to optimize the TCSC parameter. With PSO optimized TCSC, the value of 1-SM for the system is reduced to 0.932 from 0.945. While HPSOGWO optimizes the TCSC parameter to reduce the value of 1-SM for the system to 0.925, which is the best value obtained out of the three algorithms.

### 5.10.2 Outage of Line Number 12

The calculated value of 1-SM changes from a base value of 0.945 to the corrected value of 0.921 when GWO optimizes the TCSC parameter, with an outage of the line between 6-10. The value of 1-SM decreases from 0.945 to 0.926 when PSO is used to change the TCSC parameter and with HPSOGWO the value of 1-SM is upgraded to 0.856

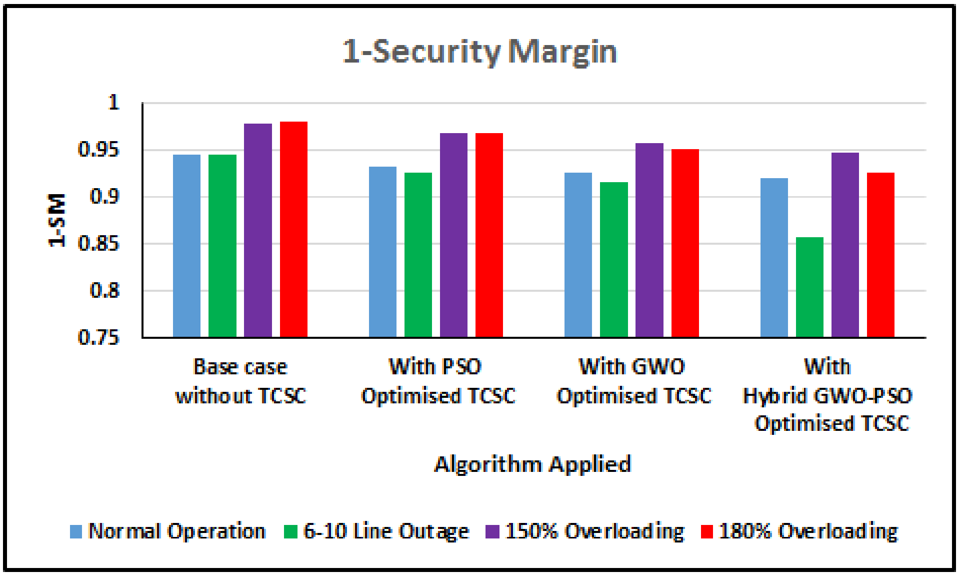

Figure 5.9 Comparative display of reduction in 1-SM without TCSC and with TCSC

### 5.10.3 Overloading of The System By 150%

Now the system is overloaded by 150%, the value of 1-SM without TCSC increases to 0.977. GWO optimized TCSC corrects this value of 1-SM to 0.956 from the enhanced value of 0.977. On the other hand when PSO is optimizing TCSC the value of 1-SM changes to 0.968 from the base value of 0.977. This value of 1-SM is improved to 0.946 when TCSC is optimized by HPSOGWO.

### 5.10.4 Overloading of The System By 180%

The base case value of 1-SM is 0.979 when the system is overloaded by 180%. TCSC optimized by PSO improves this value to 0.967. When the TCSC is optimized by GWO, the 1-SM value is improved to 0.950. When TCSC is allocated after being optimized with HPSOGWO in the same system with 180% overloading, 1-SM changes to 0.925 improving the stability of the system.

## 5.11 LINE UTILIZATION FACTOR (LUF) REDISTRIBUTION

Figure 5.10 demonstrates the reduction in LUF when TCSC is suitably placed after being optimized by applying GWO, PSO, and HPSOGWO.

### 5.11.1 Normal Operating Condition

Without implementing TCSC, the maximum value of LUF attained at line number 18 during normal operating conditions is 0.699. This maximum LUF value is decreased to 0.604 on line 27 when GWO is applied and further decreased to 0.650 on line 30 when PSO is applied. TCSC optimized with HPSOGWO redistributed LUF and the maximum value of LUF obtained is 0.555 in line 27. Here we can see that the LUF gets rearranged after TCSC is implemented i.e. the overloaded lines get relaxed and the underloaded lines are loaded optimally to reduce the congestion on heavily loaded lines.

### 5.11.2 Outage of Line Number 12

When the line between 6-10 is out, the maximum value of LUF obtained increases to 0.836 from a normal value of 0.699, in absence of TCSC at line number

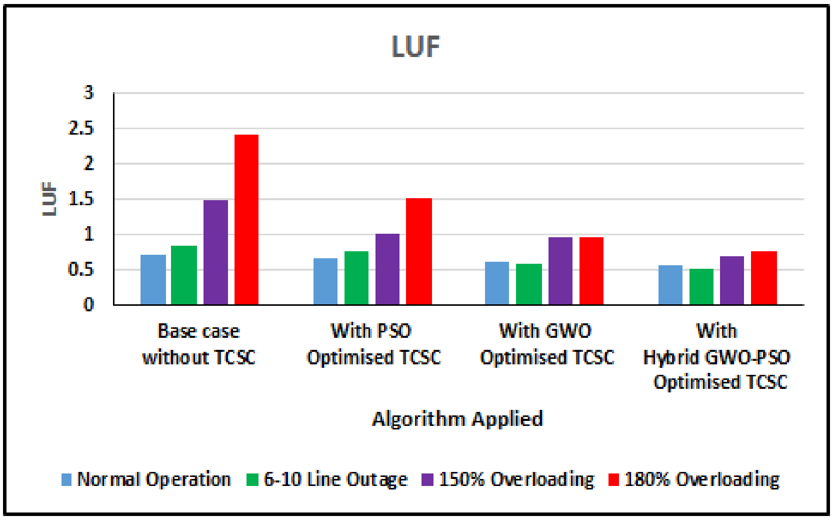

**Figure 5.10 Reduction in Line Utilization Factor with and without TCSC**

18. With the application of GWO maximum value of LUF is decreased to 0.587 at line number 27. The maximum value of LUF decreased to 0.604 on the same line 27 when TCSC placed is optimized using PSO. HPSOGWO optimized TCSC when located in the system the maximum LUF value reduces to 0.503. Hence the LUF values are redistributed to mitigate congestion.

### 5.11.3 Overloading of The System By 150%

Overloading of the system by 150% is a very bad condition of the power system in comparison to a single line outage. In this case, the maximum value of LUF is increased to 1.47. This represents a bad state of congestion. TCSC optimized with GWO reduces the maximum value of LUF to 0.956 at line 18. While PSO optimized TCSC decreases the maximum value of LUF to 1.01 which is yet again a state of congestion. So the net LUF of the line is reduced but the system is still working under stressed conditions of congestion. When the TCSC parameter is attuned by HPSOGWO, shows the relived condition as the maximum value of LUF reduces to 0.666.

### 5.11.4 Overloading of The System By 180%

Overloading the system by 180% is the nastiest condition of the power system among all other contingencies considered here. The maximum value of LUF is enhanced to 2.41 at line 1 without the implementation of TCSC. When parameter optimized with PSO, TCSC reduces the maximum value of LUF to 2.22 at line 7, which is again a condition of heavy congestion. GWO optimized TCSC reduces the maximum LUF value to 2.11 in the same line 7. So it is very clear that neither GWO nor PSO are able to reduce congestion when applied independently. This requires the hybrid of the two i.e. HPSOGWO to reduce the maximum value of LUF to a safe value. In this case, the LUF value is reduced to 0.962 which significantly alleviated congestion.

## 5.12 COMPARISON OF RESULTS OBTAINED BY DIFFERENT ALGORITHMS

### 5.12.1 Active Power Loss Reduction

Figure 5.11 gives a detailed comparison of active power loss reduction achieved by different algorithms applied. As compared to the system without TCSC, GWO optimized TCSC when implemented in the system real power loss is decreased by 4.28 %. The analogous percentage reduction in active power loss by TCSC optimized by PSO is 3.43 %. Correspondingly, with the application of TCSC optimized by HPSOGWO the percentage of active power loss reduction 4.89 % as compared to the base case.

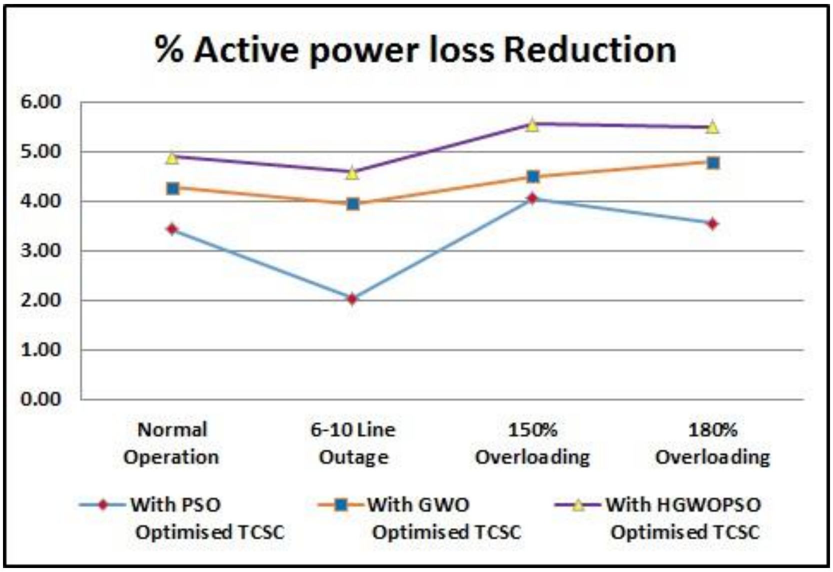

Figure 5.11 Percentage of active power loss reduction by different methods

When considering the outage of line number 12, it can be seen from Figure 5.11 that with GWO optimization the percentage reduction in active power loss is 3.94%, with PSO optimization the decrease is 2.03 %, and with HPSOGWO optimization applied for TCSC parameter manipulation this reduction is 4.59%. Under 150% overloading, the decrease in active power loss is 4.50% with TCSC optimized with GWO. The percentage reduction falls to 4.04 % when PSO is operated to optimize TCSC and the percentage reduction increases to 5.54% when TCSC is placed appropriately by applying HPSOGWO.

When the system is subjected to 180% overloading with PSO optimized TCSC the active power reduction is 3.5% which further increases to 4.9% with the implementation of GWO optimized TCSC in the system. This percentage reduction in power loss is increased to 5.48%, which is the best of the three algorithms. Thus Figure 5. 11very well establishes the effectiveness of HPSOGWO in optimizing TCSC parameters to reduce active power loss more efficiently in comparison to GWO & PSO used optimized TCSC independently.

### 5.12.2 1-SM Improvement

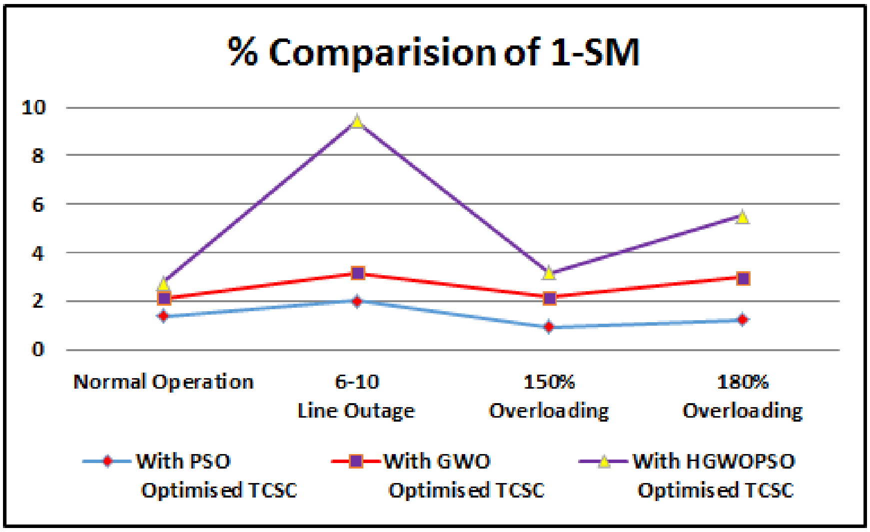

Figure 5.12 Percentage 1-SM improvement by different methods

Figure 5.12 establishes a comparison of the percentage improvement in system security margin. In the base case when GWO optimized TCSC is implemented in the system improvement in 1-SM is 2.11%. Improvement in 1-SM value with PSO optimized TCSC is 1.37% and with HPSOGWO the percentage improvement is 2.75%.

The value is further enhanced to 3.02% when GWO optimized TCSC is installed in the system. HPSOGWO optimized TCSC upgrades the % of 1-SM by 5.75%.

### 5.12.3 Reduction in Voltage Deviation

The reduction in voltage deviation during the working of a transmission system with power flowing during diverse emergency conditions displays the stability of the system.

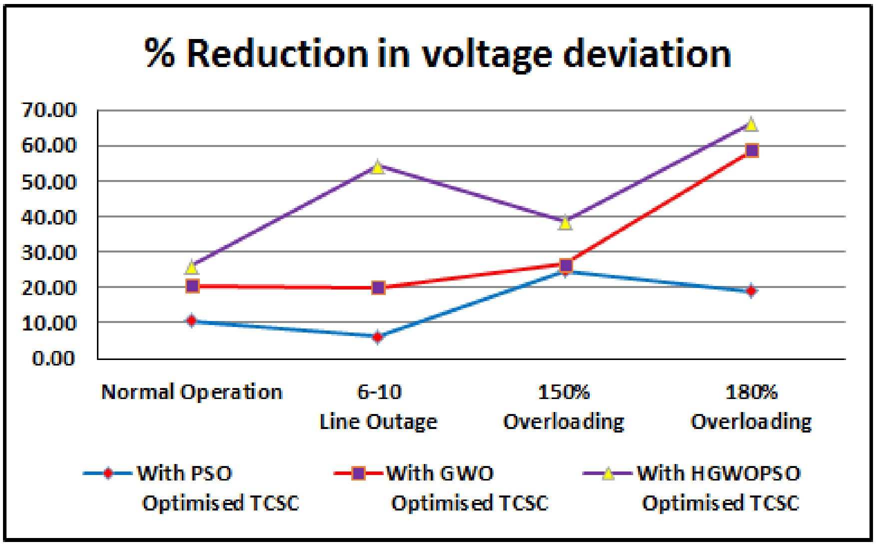

Figure 5.13 Percentage Voltage deviation reduction by different methods

When outage of Line 12 is considered the improvement in 1-SM value is 3.17 % upon optimizing TCSC with GWO and the value is 2.01% when PSO is applied. There is a significant improvement in 1-SM to 9.41% when HPSOGWO is applied to optimize TCSC.

When the system is subjected to 150% overloading, the 1-SM value is upgraded by 2.14% with GWO applied for TCSC parameter adjustment and improves to 0.92% with PSO. The improvement 5.51% in 1-SM when HPSOGWO is applied to optimize TCSC. TCSC parameter when optimized with PSO in the condition when the system is overloaded by 180%, the 1-SM value is enhanced by 1.08%. Figure 5.13 displays a reduction in percentage Voltage deviation when GWO, PSO, and HPSOGWO optimized TCSC is implemented in the system for different emergency conditions like line outage and overburdening of the power system. With TCSC optimized by PSO under base conditions, the reduction in percentage voltage deviation is 10.71% while this reduction value is enhanced to 20.54% when TCSC is optimized by GWO. HPSOGWO optimized TCSC gave a better reduction in voltage deviation, which approximately is 25.98 %. The effect of the line 12 outage is displayed in Figure 5.13 with TCSC incorporation after being allocated and optimized by GWO, PSO, and HPSOGWO.

With GWO optimization the reduction in percentage voltage deviation is 20% whereas it is only 6.14% with TCSC optimized with PSO. When the system is optimized by HPSOGWO for the setting of TCSC parameters. Percentage voltage deviation is decreased by 54% which is quite a significant value during line outage.

Figure 5.13 also displays the results for the emergency condition of 150% overloading of the system. The percentage deviation in voltage is decreased by 26.54% with GWO optimization whereas it is decreased by 24.5% with TCSC optimized with PSO as compared to normal working conditions. The deviation is further significantly decreased by 38.5% when the TCSC parameter is set by the application of HPSOGWO. System subjected to 180% overloading when implemented with PSO optimized TCSC the voltage deviation is reduced by 20% and the percentage reduction is enhanced to 60% with GWO optimized TCSC. While this percentage reduction further enhances to 65% with TCSC optimized by HPSOGWO.

### 5.12.4 Reduction in LUF By Different Methods Adopted

Figure 5.14 displays the percentage decrease in the maximum value of LUF due to different emergency conditions. During base conditions with the use of GWO for parameter optimization, the percentage reduction in the maximum value of LUF is 13.59% as compared to the base case value. With PSO maximum reduction in the percentage value of LUF is 7%. With the application of HPSOGWO to optimize TCSC the percentage reduction in the maximum value of LUF is 20.74%.

Figure 5.14 also shows a percentage reduction in the maximum value of LUF with an outage of line 12. With GWO optimization 29% decrease in maximum LUF value is attained while with PSO this value reduces to 10.89%.

Maximum percentage reduction in LUF is obtained with the optimization of the TCSC parameter with HPSOGWO. This decrease in percentage values is 40% to than the LUF value that caused congestion in line. When lines are overloaded by 150%, GWO optimization decreased maximum LUF by 34% in contrast to 31% obtained by optimization with PSO. With HPSOGWO optimization the percentage reduction in the maximum value of LUF becomes 54%.

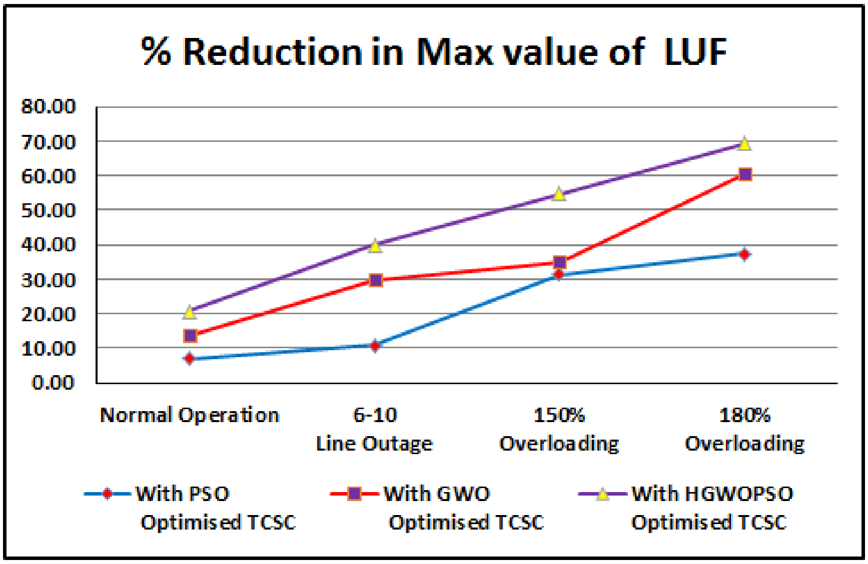

Figure 5.14. Reduction in the maximum value of LUF by different methods adopted

Table 5.6 elaborates on the results obtained by the application of different algorithms.

**Table 5.6 Consolidated results for Multi-objective function applied on IEEE 30-Bus system**

| **Contingency Conditions** | **With no TCSC** | | | | **With TCSC** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | **PSO** | | | | **GWO** | | | | **HPSOGWO** | | | |
| | **Max LUF** | **PL (MW)** | **VD (p.u.)** | **1-SM** | **Max LUF** | **PL (MW)** | **VD (p.u.)** | **1-SM** | **Max LUF** | **PL (MW)** | **VD (p.u.)** | **1-SM** | **Max LUF** | **PL (MW)** | **VD (p.u.)** | **1-SM** |
| **Normal Operation** | 0.699 | 6.85 | 0.011 | 0.945 | 0.65 | 4.5 | 0.01 | 0.932 | 0.587 | 3.92 | 0.009 | 0.925 | 0.554 | 3.5 | 0.008 | 0.919 |
| **Single Line Outage** | 0.836 | 6.93 | 0.011 | 0.945 | 0.745 | 5.52 | 0.011 | 0.926 | 0.604 | 4.2 | 0.009 | 0.915 | 0.503 | 3.75 | 0.005 | 0.856 |
| **150% Overloading** | 1.47 | 24 | 0.032 | 0.977 | 1.01 | 14.3 | 0.024 | 0.968 | 0.956 | 13.2 | 0.024 | 0.956 | 0.666 | 10.7 | 0.02 | 0.946 |
| **180% overloading** | 2.41 | 56 | 0.126 | 0.979 | 1.51 | 36.1 | 0.102 | 0.967 | 0.956 | 29.2 | 0.052 | 0.95 | 0.742 | 25.2 | 0.043 | 0.925 |

## CONCLUSION

Multi-objective function including power loss reduction, voltage deviation reduction, improvement of security margin and redistribution of power flows through the transmission lines is being achieved for mitigating congestion with the implementation of TCSC has been illustrated. TCSC being located with the help of DLUF. A comparative analysis of the results obtained with the implementation of GWO, PSO, and HPSOGWO has been done. At normal operating conditions the overall power loss is reduced by 34%, 42%, and 48% respectively when TCSC optimized with PSO, GWO, and HPSOGWO is incorporated in the system. Similarly, other parameters are optimized and show better results with HPSOGWO in comparison to the parent algorithms. Congestion is thus mitigated with reduced power loss and voltage deviation. The security margin has been improved significantly.

# CHAPTER VI

# OPTIMAL RESCHEDULING OF GENERATOR TO ALLEVIATE CONGESTION USING HYBRID PSO-GWO

## 6.1 INTRODUCTION

Deregulation strategies and privatization of the power system is the primary reason that has introduced congestion in today’s power system. To supply the increased load, the lines are working near voltage and thermal limits and hence are severely stressed. By working under such conditions power system reaches the verge of thermal instability. In deregulation, vertically integrated utilities of the power system have reformed from both the generator/utility end and consumer end [140]. The deregulation has been implemented to give maximum/ attractive profit to the private participating generators and distributors which may give inspiration for power generation. These policies resulted in the enhancement of power generation by many folds but also increased the load on some of the lines of the system creating congestion. The congestion is in terms of violated maximum and minimum bus voltages, maximum thermal limits, and security restrictions [141]. For the system to be stable and reliable, the congestion has to be mitigated. Cost-free methods and non-cost-free methods are two basic methods for alleviating congestion in power systems. Implementation of FACTS devices comes under a cost-free method. This method does not involve any operational cost so considered a cost-free method. Generator rescheduling and load curtailment involve the cost of changing the output of the generator in the form of operational cost thus, considered a non-cost-free method [142].

Numerous approaches and methodologies have been suggested in the literature which is an effective way to mitigate congestion. But the cost of rescheduling of generator which is also termed congestion cost is the main problem incrementing the overall cost of power. The rescheduling helps to mitigate congestion efficiently but increments the cost of rescheduling generator output while if the cost of rescheduling is maintained the congestion is not alleviated. This chapter deals with the implementation of a process that carries out congestion mitigation keeping the cost of congestion as low as possible with the least variation in terminal real power output of the generators. This chapter implements a methodology for rescheduling the active power of generators in a congested system so as to relieve the overloaded lines. GSF has been used to find out the generator participating in the process of rescheduling. After generators are selected, with the purpose of minimizing the cost of congestion, the terminal active power for specified generators is rescheduled. A novel method to combine GWO and PSO to get a hybrid i.e., HPSO-GWO is proposed here for optimally rescheduling the participating generators. HPSO-GWO has given better performance as compared to the parent algorithms.

The sensitivity index approach has been used to reschedule the generator and curtailment of the load to mitigate congestion. The sensitivity index gives the sensitivity of current flowing through a line to a change in bus injection [143]. With the important issues of system stability and control of electricity prices in deregulated markets, congestion management has been an issue that is to be treated with first preference. A congested power system results in an accountable amount of power loss, which in the end falls on the customer's account.  Numerous methods to mitigate congestion have been explored and authenticated on diverse types of power systems [144]. Work has been done on different methods to mitigate transmission congestion which in turn is due to deficient power system infrastructure and day by day increasing demand. PSO with Time-Varying Acceleration Coefficients (PSO-TVAC) is proposed to search the most suitable generator for re-scheduling the output power with minimal rescheduling cost [145]. Different meta-heuristic optimization techniques like Fuzzy Evolutionary Programming (FEP) and NDS-GA have been applied to mitigate congestion in power systems [146]. Optimizing generator output and congestion cost minimization, the ABF algorithm with Nelder–Mead (ABFNM) has been proposed to assure reliability in power systems and availability of power to the consumers at a reduced cost [147]. Rescheduling of generators has been carried out with the help of Fuzzy adaptive bacterial foraging (FABF) for managing congestion. The selection of individual generators to participate in the rescheduling process is carried out with GSF. It is the sensitivity of a line to a change in generator output [148]. To combine congestion cost index and DG installation cost with line losses a real coded GA has been proposed. With the help of this method system operator is free to choose a solution that will depend on the extent of congestion and the priority of the condition [149].  MO Genetic Algorithm is advised to interpret the Voltage Stability Constrained

OPF. TCSC and SVC are optimized for parameter sizing and placement together with generator rescheduling for voltage control and low-price FACTS devices [150]. When congestion occurs, the generators and buyers of electricity together try to equate the supply and demand. In doing so safety and dependability of the system are undesirably impacted. To enhance the security and reliability of the system concerned, the generators are rescheduled by applying GA with the objective to minimize the rescheduling cost of the generators [151]. Hybrid PSO with improved time-varying acceleration coefficients (PSO-ITVAC) has been reported to minimize the cost of active power rescheduling of the participating generator [152]. Voltage stability and line loading constrained FA is proposed to mitigate transmission congestion in a pool market, by obtaining minimal cost for rescheduling generator output [153]. A fuzzy inference system (FIS)-based algorithm has been proposed to designate the overburdened transmission line. Sensitivity factors like overload factors and transmission congestion distribution factors (TCDF) are implemented here to get an indication of the congested line [154]. Generators are rescheduled for real power by implementing an Ant Lion Optimization (ALO) algorithm to mitigate congestion. Again, the sensitivity of a generator for a particular congested line is taken as the base to select the generator to participate in the rescheduling process [155]. Location marginal pricing (LMP) has been used as a sensitivity factor to reschedule generators for their active power. GA is used to reschedule the generator to alleviate congestion in the system [156]. The stressed/overloaded lines can be relieved by either load curtailment or by generator rescheduling and in some cases both by generator rescheduling together with the load curtailment. This chapter emphasizes the rescheduling of the generator without load curtailment to reduce the cost of rescheduling i.e. congestion cost and mitigating congestion. The generator when rescheduling the generation it results in an increased cost of fuel and other charges thus generator rescheduling is considered one of the non-cost-free methods to alleviate congestion. Selection of the generators which will be participating in the rescheduling process is done by generator sensitivity factors (GSF) while the amount of rescheduling for economic output with congestion mitigation is done by applying HPSOGWO. The output of generators is optimized by the proposed HPSOGWO to minimize the generator active power output deviation also apart from reducing cost. Afterward, HPSOGWO is applied to minimize congestion costs together with the reduction in system losses. The effectiveness of the proposed merging of PSO and

GWO algorithm confirms the outperformance of the proposed method over GWO and PSO.

## 6.2 METHODOLOGY ADOPTED

### A) Grey Wolf Optimizer

***GWO Algorithm***

```
Initialize grey wolf population of (n=100)
&& a, A and C
Set iteration count, t=0
Estimate fitness value for all wolves
sort for three best values
    if  iteration == $itr_{max}$
            $\vec{X}_{GW}(t+1)$ is the solution
        else reduce the value of 'a'
evaluate new values of A and C by applying
            $a(iteration) = 2 * iter\_count(\frac{2}{itrmax})$
    find updated values of $D_a$, $D_b$, and $D_g$
    Apprise the location of each solution
            if  $\vec{X}_{GW}(t) == \vec{X}_{GW}(t+1)$
                    stop iteration
                else increment iteration counter
                    t=t+1
        End
    End
```

### B) Particle Swarm Optimizer

The social behavior of fish schooling or bird flocking is the elementary principle to develop PSO. This is a population-based stochastic optimization technique [157]. Food exploring the behavior of birds' flocks is the basic technique applied in this optimization technique. In search of food, the bird follows the path for getting a minimum distance from food, the same path is followed by all other members of the flock. The ‘members’ in the algorithm are really the fitness values of the objective in the solution exploration space. The ‘solutions’ are called ‘particles.’ The suitability of each particle is assessed by a fitness function while the velocity of particles decides the course of flying. The optimal position is the particle closest to the solution while its velocity is counted as the optimum velocity for all.

Initialization of the algorithm is executed by assuming an arbitrary number of particles in the search space and the best position is estimated by updating generations. The two best positions are obtained with repeated iterations. Sorting the best position from all the new positions obtained is the current best position of the particle. Global best position ($g_{best}$) is another best position obtained by other neighbouring particles. When the topological position of its neighbourhood particle is taken by a particle it is called its local best position ($P_{best}$).

The apprised particle position and its velocity are given by:

$$\left.\begin{gathered} v_t = V_t + 2 * rnd * [p_b(t) - t] + 2 * rnd * [g_b(t) - t] \\ t = t + V_t \end{gathered}\right\} \tag{6.1}$$

Where

$v_t$ : represents the preceding velocity,

$p_b$ : represents the finest position particle have realized,

$g_b$ : represents the global best position particle has realized.

```
PSO Algorithm

for each particle, initialize the particle
    Initialize the population, n
for all particles
    Calculate f( $p_b$ ) and f( $g_b$)
      Update the velocity, $v_t$
      Update the position    t-t+$v_t$
Do apply the limits
   if  $v_t \geq v_{tmax}$
```

```
          put $v_t = 0$
          if $t \geq t_{max}$
               put $t = t$
          else calculate $f = fun(t)$
for $f < func(p_b)$
     Set $p_b = g_b$
     End
End
```

### C) Merged PSO-GWO

**Pseudo code for Hybrid PSO-GWO**

```
Create population randomly
Set a small probability rate : p
Fix maximum iterations and initiate iteration count itr=0
Run PSO for fitness evaluation of all particle
Sort and index fitness of each particle
if itr = itr_max
    Stop
    else update particle velocity and position
end if
for current particle
    if rand(0,1) < p , then set the values
    a, A & C (for avoiding local minima)
```

```
        else run PSO for fitness evaluation
      of all particle
      end if
    Evaluate the fitness of all wolves
    Update Xa, Xb, and Xg
        if itr < $itr_{max}$
            Calculate X(t+1)
            Substitute this position to PSO
      particles
            Run PSO
            else update the position of the
      wolf
        end if
    end for
```

## 6.3 PROBLEM FORMULATION

Generator Sensitivity Factor (GSF) is applied here for the determination of the generators that will actively contribute to the process of active power rescheduling. GSF represents the sensitivity of a specific generator for an overloaded line. GSF can be described as the relation between variation in the real power flow in a line between two buses and a unit change in the real power output of a particular generator [158]. GSF is calculated for a line m based on the AC load flow approach, between bus *k* and bus *l*. The expression for real power flow between corresponding buses can be written as:

$$P_{kl} = Y_{kl}[V_k V_l \cos(\emptyset_{kl} + \theta_k - \theta_l) - Y_{kl} cos\emptyset_{kl} \quad (6.2)$$

As the real power transacted between $k$ and $l$ is voltage constrained function at the respective buses i.e., $V_k\,, V_l$ and their equivalent angles i.e., $\theta_k, \theta_l$. So, real power flow can also be expressed as:

$$P_{kl} = f\left(V_k, V_l, \theta_{k,} \theta_l\right) \tag{6.3}$$

With the intervention of contingencies in the power system, the change in the active power flow inline $m$, can be represented in equation (6.4).

$$\Delta P_{kl} = f\{(V_k^0 + \Delta V_k), (V_l^0 + \Delta V_l)(\theta_k^0 + \Delta\theta_k)(\theta_l^0 + \Delta\theta_l)\} - P_{kl}^0 \tag{6.4}$$

Where,

$P_{kl}^0$ : is the initial active power flow before the contingency

$V_k^0, V_l^0, \theta_k^0$ $and$ $\theta_l^0$ : Corresponding voltage magnitude and angles

The modified active power can be written as:

$$P_{kl} = P_{kl}^0 + \Delta P_{kl} \tag{6.5}$$

Equation (6.5) can be re-written as:

$$\Delta P_{kl} = p_{kl}\Delta\theta_k + q_{kl}\Delta\theta_l \tag{6.6}$$

Where,

$p_{kl}$ $and$ $q_{kl}$ : Coefficients evaluated by partially differentiating equation (6.3) with respect to $\theta_k$ $and$ $\theta_l$ respectively.

As voltage variation has no significant effect on real power transmission through the line so the effect of change in voltage is neglected here. Now, when the real power output of the generator is altered by $\Delta PG_n$, load flow analysis is performed to calculate the new power flowing flow in line $m$. Then the variation in the real power flow in line $m$ is calculated to get the value of GSF.

Mathematically, GSF now can be calculated by obtaining the ratio of variation in the real power flow in line $m$ between bus $k$ and $l$ for a small change in real power, $\Delta PG_n$, in n$^{th}$ generator, GSF can be given as:

$$GSF_n^m = \frac{\Delta P_{kl}}{\Delta PG_n} \tag{6.7}$$

$GSF_n^m$ represents the sensitivity of line $m$ to change in bus real power injection by generator $n$.

The GSF value for all congested lines for each generator is calculated. Whenever there is an alteration in generator real power output the congested line becomes more congested or there is a relief in congestion. With increased congestion, the value of GSF obtained will be negative which means that a particular congested line is showing higher sensitivity to a particular generator. Positive values of GSF are neglected. The generators with high negative and uneven values of GSF will be affecting the real power flow through the congested lines. The generators showing the negative and non-uniform values are the ones to be a part of the re-scheduling process for congestion management.

Each generator has an increment/decrement cost bid which is supplied to the system operator (SO). Thus, the cost of rescheduling is the base for mitigating congestion here. In general, case, when congestion is mitigated by rescheduling the cost to reschedule, is enhanced making the system uneconomical. On the other hand, when the cost is the target objective the congestion is not mitigated effectively. Here the objective function is formulated with an objective to mitigate congestion but at a minimum cost of rescheduling or cost of congestion.

Thus, the objective function as an optimization problem can be formulated as:

$$f(CC) = minimize\left( \sum_{n=1}^{N} C_{bn}(\Delta PG_n) \times \Delta PG_n \right) \tag{6.8}$$

In equation (6.8)

$\Delta PG_n$ : change in real power output for n$^{th}$ generator

$C_{bn}$ : congestion costing bid (CCB) offered by nth generator

N : number of generators participating in rescheduling.

CCB is the maximum active power generation a generator can willingly increase with additional charging to mitigate congestion.

The constraints applied to solve the optimization problem formulated are shown in Table 6.1. Power flow inequality and equality limitations, bus voltage constraints, generator voltage constraints, real power constraints of generators, and GSF restrictions are taken into account. In case the constrained values are out of limits, the predefined limits are followed for the system to be stable.

**Table 6.1 Limitations applied**

| S No | Constraints | Analytical Equations |
|---|---|---|
| a | Generator Sensitivity Factor | $\sum_{n=1}^{N}((GSF_n) \times \Delta PG_n) + P_i^0 \leq P_i^{max}$ |
| b | Deviation in Generator real Power | $\Delta PG_n^{min} \leq \Delta PG_n \leq \Delta PG_n^{max}$ |
| c | Real Power | $P_{gn} - P_{dn} - P_n(V_n, \theta_n) = 0$ |
| d | Generated Active Power | $P_{gn}^{min} \leq P_{gn} \leq P_{gn}^{max}$ |
| e | Bus Voltage | $V_{nmin} \leq V_n \leq V_{nmax}$ |

## 6.4 RESULTS AND ANALYSIS

In this chapter, the methodology proposed is authenticated on IEEE 30-Bus system [159] using MATLAB 2016a as shown in Figure 6.1.

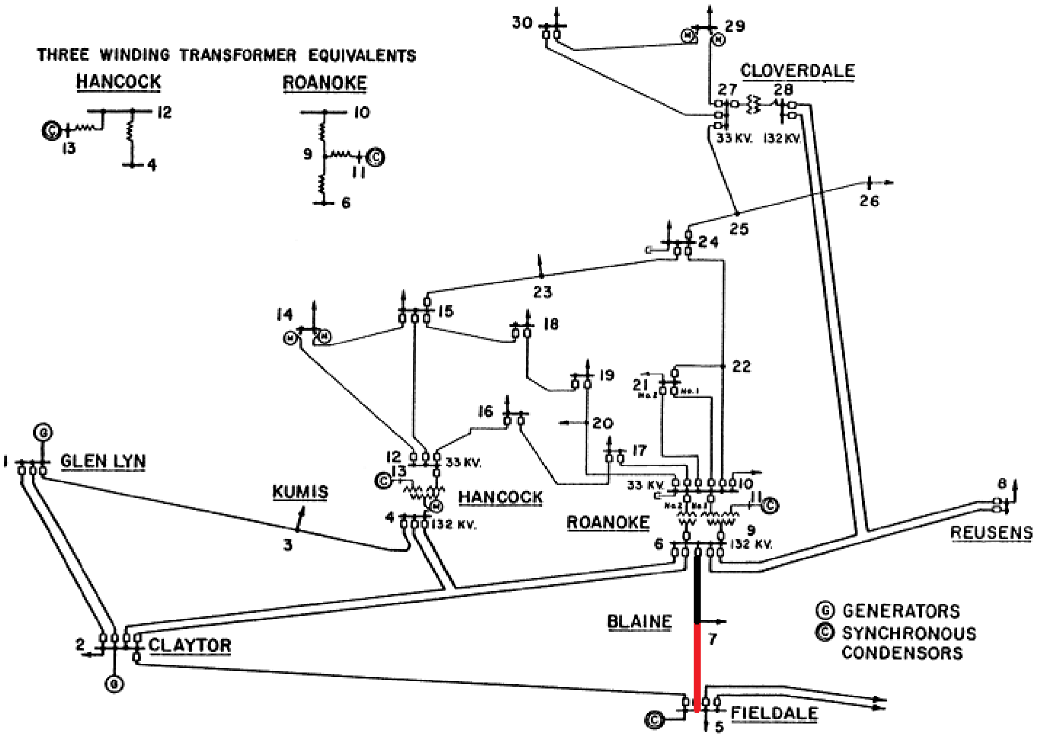

**Figure 6.1: Standard IEEE 30-Bus system [159]**

The system comprises a slack bus generator with 5 other generators and 41 transmission lines. The system is simulated for HPSOGWO, PSO, and GWO, and the results obtained are compared. The comparison shows that HPSOGWO more effectively solves the objective formulated as compared to GWO and PSO. The system is tested for N-1 contingency where a single line outage between5-7 is done. Figure 6.2 shows the details of line flows before and after the contingency. Here the congested lines after the outage can be marked distinctively as compared to the base case.

Congestion in lines 1,5, 18, 19, 21, 30, and 40 can be seen in Figure 6.2 subject to the outage of line number 12. These lines are to be relieved from congestion by re-scheduling the real power output of generators. The participating generators in the process of rescheduling are attained by using GSF. Load flow analysis is performed when the output of one of the generators is incremented by 1MW and keeping all other generators working at their rated real power capacity. This will give the altered line flows in the lines and the increment/decrement in the line flows is calculated. Equation (6.8) is then implemented to calculate all values of GSF for the generator. Figure 6.3 illustrates line flows with change in active power output of generator number 2 by 1 MW.

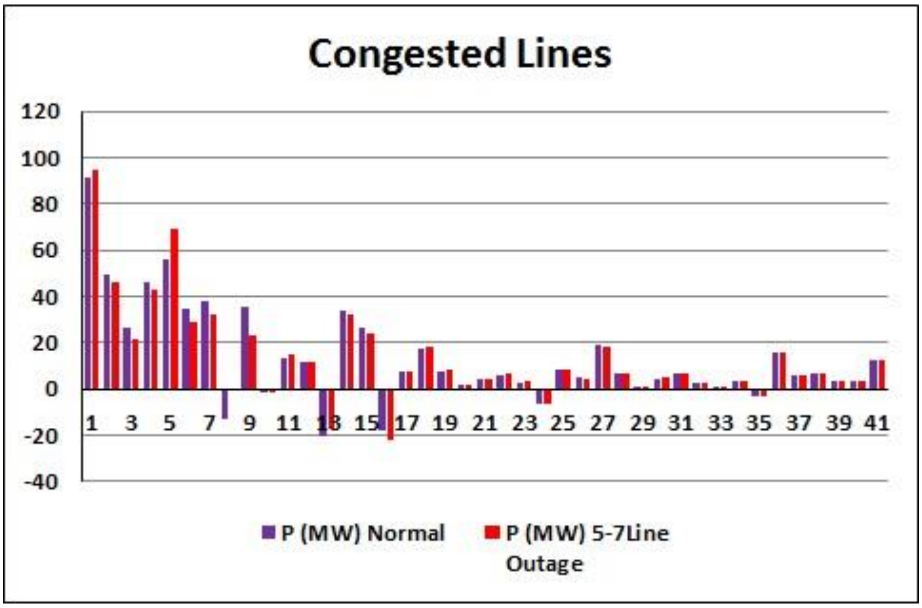

**Figure 6.2 Congested lines with N-1 contingency at line 12**

Figure 6.4 depicts line flows with change in active power output of generator number 5 by 1 MW. Similarly, Figure 6.5, Figure 6.6, and Figure 6.7 illustrate the line flow values for 1 MW transaction by generator numbers 8,11, and 13 respectively.

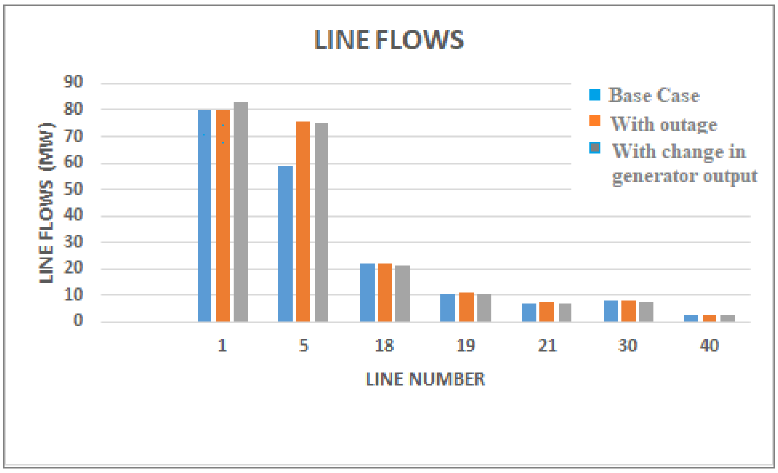

Figure 6.3 Line flows with change in output of generator number 2

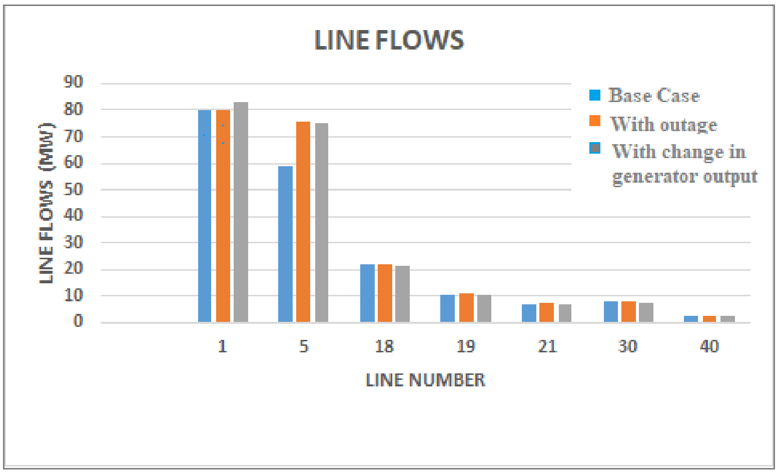

Figure 6.4 Line flows with change in output of generator number 5

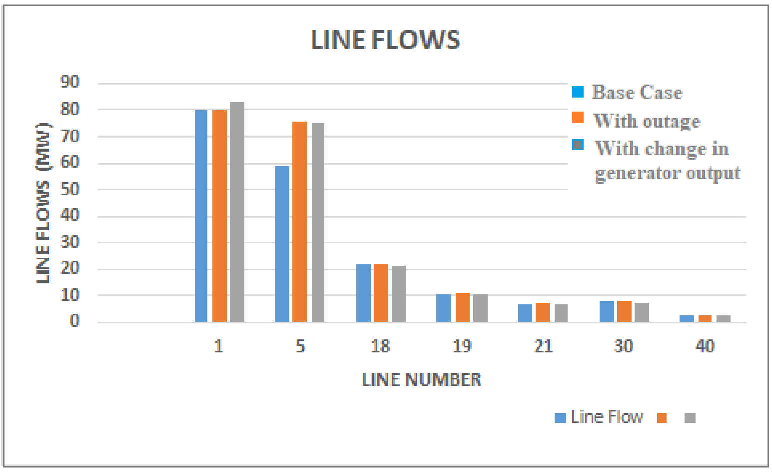

Figure 6.5 Line flows with change in output of generator number 8

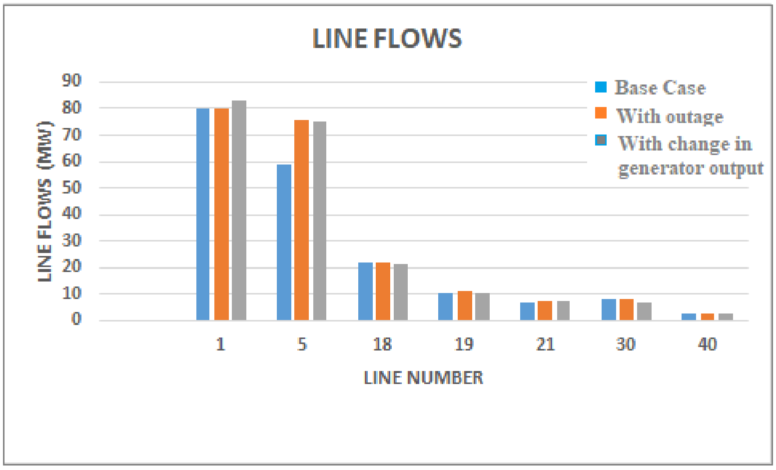

Figure 6.6 Line flows with change in output of generator number 11

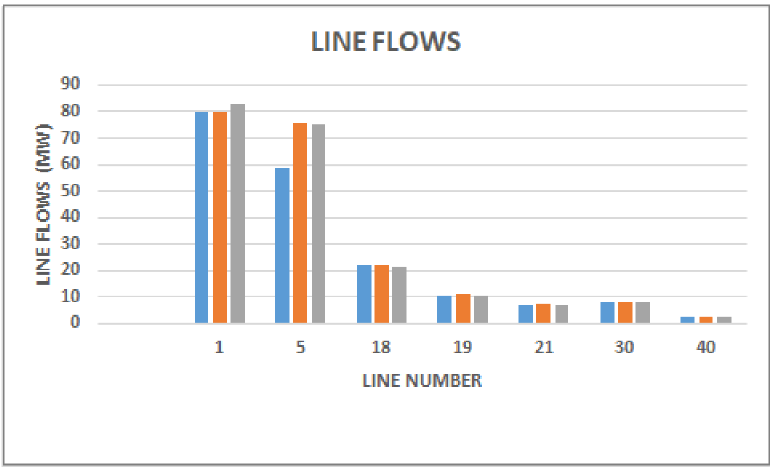

Figure 6.7 Line flows with change in output of generator number 13

Figure 6.8 shows the GSF variations for different generators for the congested lines.

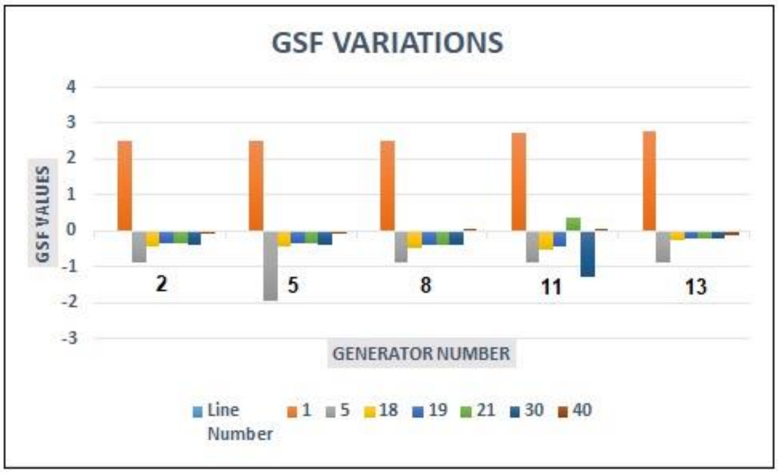

Figure 6.8 GSF variations for all generators

The generator with maximum negative and non-uniform values of GSF will be qualified to contribute in the process of rescheduling as the congested lines will show the highest sensitivity to these generators

GSF values obtained for generators 2, 5, 8, 11, and 13 are illustrated in Figure 6.8. These GSF values are sorted for most negative and non-uniform values. These sorted values are shown in Table 6.2. Large negative GSF values of generators show that the real power flowing through congested lines is significantly affected when there is a change in the real power output of the respective generator. The generator bidding coefficients are given in Appendix A, Table A.5.

**Table 6.2 Selected GSF values of all generators by simulation**

| **Generator** | 1 | 2 | 5 | 8 | 11 | 13 |
|---|---|---|---|---|---|---|
| **GSF** | 0 | -0.89 | -1.96 | -0.89 | -1.27 | -0.89 |

**Table 6.3 Consolidate results for scheduled generations before and after CM**

| **Generations** | **During Congestion (MW)** | **After congestion is mitigated (MW)** | | |
|---|---|---|---|---|
| | | **PSO [23]** | **GWO** | **HPSOGWO** |
| $PG_2$ | 62.96 | 68.3 | 49.74 | 47.59 |
| $PG_5$ | 20.76 | 22.88 | 37.27 | 37.75 |
| $PG_8$ | 27.80 | 34.42 | 23.76 | 25.91 |
| $PG_{11}$ | 19.52 | 19.93 | 20.45 | 18.87 |
| $PG_{13}$ | 39.7 | 22.05 | 39.51 | 35.53 |

The values of planned power generations before and after CM are presented in Table 6.3. Calculated active power of generators after rescheduling and comparison between PSO [23], GWO and HPSOGWO is shown in Table 6.3.

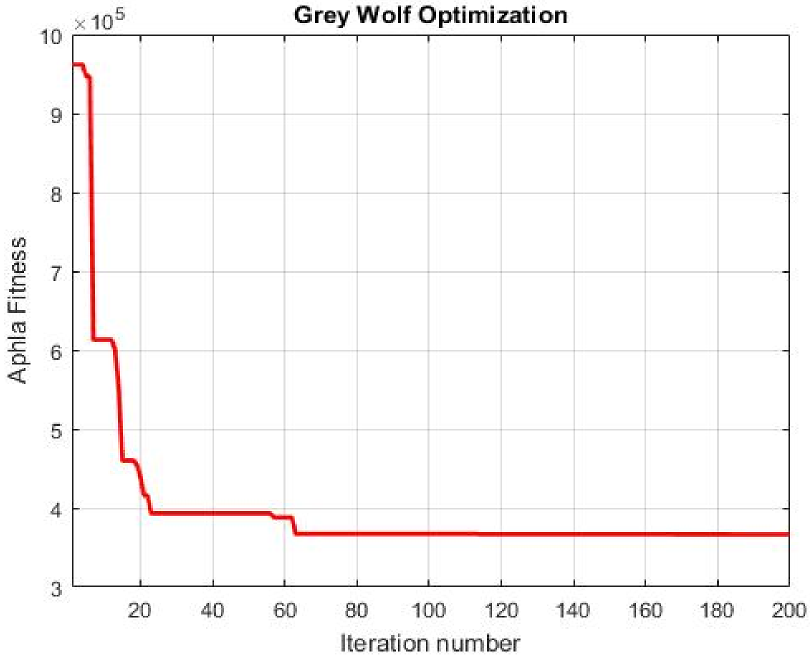

Figure 6.9 Convergence Characteristics for GWO

The convergence graph for GWO, PSO, and HPSOGWO has been illustrated in Figures 6.9, 6.10, and 6.11. It can be seen that with GWO, OPF requires 62 iterations to converge, while PSO converges in 75 iterations and HPSOGWO requires 22 iterations to converge.

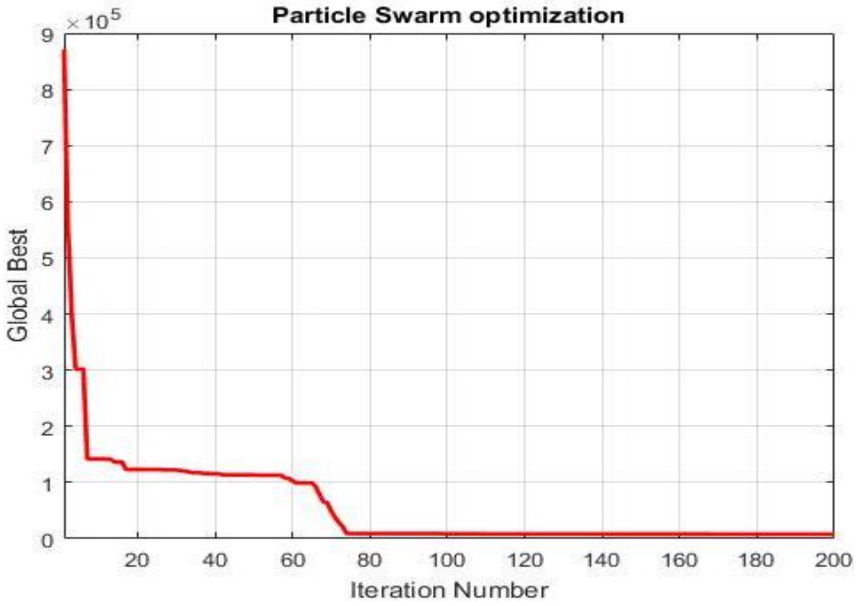

Figure 6.10 Convergence Characteristics for PSO

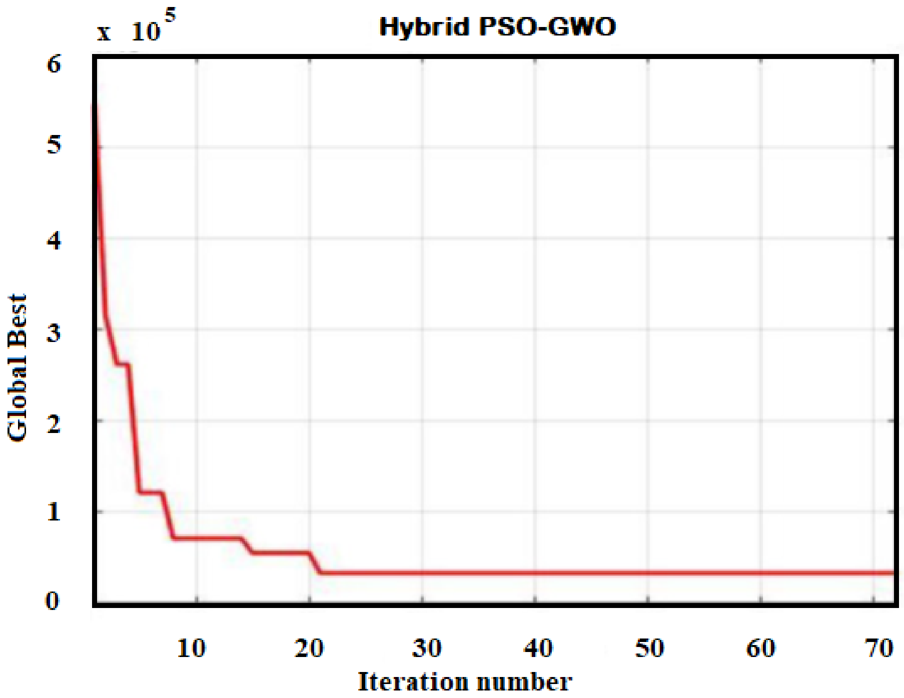

**Figure 6.11 Convergence Characteristics for Hybrid PSO-GWO**

Table 6.4 elaborates the results for the test system optimized by the implementation of PSO, GWO, and HPSOGWO. From Table 6.4 it can be seen that the CC obtained with the proposed hybrid methodology is markedly lower than that obtained by the parent algorithms. Also, the least magnitude of rescheduled active power is obtained in the case of HPSOGWO. The efficacy of the proposed method to combine the algorithms is justified by the number of iterations taken to converge.

**Table 6.4 Congestion cost, active power rescheduled, and iteration count for IEEE 30-Bus system**

| Outputs | PSO | GWO | HPSOGWO |
|---|---|---|---|
| Cost of Congestion (\$/MW-Day) | 8664.30 | 10774.35 | 8036.24 |
| Real power rescheduled (MW) | 32.92 | 38.7 | 32.3 |
| Number of Iterations | 75 | 62 | 22 |

Figure 6.12 displays increment/decrement of the real power output of the generator when it is rescheduled by applying PSO, GWO, and HPSOGWO. It can be observed

that the active power output of Generator 2 changes by 13.2MW with PSO, with GWO the change is 18.47 MW and 13.36 MW with HPSOGWO.

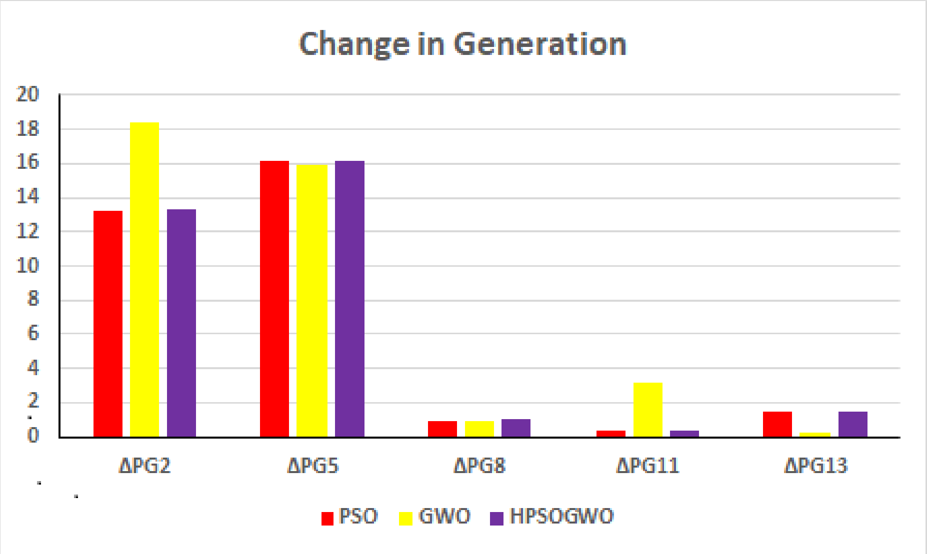

**Figure 6.12 Change in the generation when PSO, GWO, and HPSOGWO are applied**

Similarly, for Generator 5 when rescheduling is done by PSO, GWO, and HPSOGWO its output power is deviated by 16.15 MW, 15.9 MW, and 16 MW respectively. Similarly, Generator 8 deviates its output power by 0.94MW, 0.91 MW, and 1 MW while Generator 11 changes the active power output by 0.33 MW, 3.19 MW, and 0.30 MW with PSO, GWO, and HPSOGWO respectively.

**Table 6.5: Results for power flow in congested line before and after CM**

| **Line No** | **P (Normal)** | **P (line 12 Outage)** | **P (after CM)** | | |
|---|---|---|---|---|---|
| | | | **GWO** | **PSO** | **HPSOGWO** |
| | **(MW)** | **(MW)** | **(MW)** | **(MW)** | **(MW)** |
| 1 | 79.83 | 80.28 | 78.9 | 80.03 | 78.77 |
| 5 | 58.69 | 75.93 | 58.4 | 59.06 | 58.79 |
| 18 | 21.74 | 21.89 | 21.7 | 21.63 | 21.66 |
| 19 | 10.67 | 10.78 | 10.6 | 10.56 | 10.6 |

| | | | | | |
|---|---|---|---|---|---|
| 21 | 7.06 | 7.17 | 7.07 | 6.93 | 7 |
| 30 | 7.98 | 8.11 | 7.99 | 7.9 | 7.91 |
| 40 | 2.52 | 2.64 | 2.51 | 2.47 | 2.52 |

When generator 13 undergoes rescheduling the output power is changed by 1.46 MW, 0.29 MW, and 1.47 MW. The rescheduling done with the help of HPSOGWO has given a total change in active power which equals 32.3 MW which is the lowest when rescheduling is done with the parent algorithms. The results are displayed in Table 6.5.

The effectiveness of the new hybrid algorithm proposed over the parent algorithms is depicted in Table 6.5. The real power flowing through previously congested lines has been rerouted to alleviate congestion after rescheduling generators with HPSOGWO, GWO, and PSO. The active power flow in the previously congested lines with HPSOGWO rescheduled generator is approximately equal to the rated active power flow during normal conditions.

## CONCLUSION

A novel method to merge two well-known algorithms is presented in this chapter. The effectiveness of the new algorithm is validated on the standard IEEE 30-Bus system. The generator participating in the process of rescheduling being very efficiently selected with the help of GSF while the magnitude of active power for which the selected generator is rescheduled is carried out with the help of the Hybrid PSO-GWO algorithm. The objective function of minimizing the cost of congestion is effectively achieved here. The respective optimized parameters are compared for GWO, PSO, and HPSOGWO where the hybrid algorithm developed evaluated the objective function most effectively and in the minimum number of iterations.

## CHAPTER VII

# CONCLUSION AND SCOPE FOR FUTURE WORKS

This thesis is written in an effort to alleviate the power system congestion problem by enhancing ATC, reduction in active and reactive power losses, reducing voltage deviation, and enhancement of security margin with the application of the FACTS device. The congestion is also mitigated here by rescheduling generators. TCSC and SVC are located with parameters optimized to reduce active & reactive power losses, regulation of voltage profile, and enhancement of ATC. The generators are selected and rescheduled for a calculated amount of real power to alleviate the congestion. OPF based on Grey Wolf Optimization (GWO), Particle Swarm Optimization (PSO), and the hybrid of GWO and PSO (HPSOGWO) is proposed and tested for validation. IEEE 30-Bus system is considered to validate the efficacy of the proposed algorithms. Following conclusions can be drawn from the research work.

### 7.1 MINIMIZATION OF POWER LOSSES BY OPTIMALLY LOCATING FACTS DEVICES

An approach for the reduction of real and reactive power loss in transmission networks is presented. The inductive components of the branch currents are reduced when capacitors are incorporated into the system, due to the rapid supply of reactive power. The active current component also decreases due to the improvement of bus voltages. This results in not only a decrease in active power loss but also reduce reactive power loss. The method presented is categorized among the heuristic methods, and the same is applied in two steps. One step helps to find the optimized location of the FACTS device while the other helps to determine the optimal size of the device. The optimized location and size of TCSC and SVC manipulate the reactance of the line in such a way that net power loss in the transmission lines decreases. The load flow analysis is carried out by applying NR method to calculate power flows and hence the losses in the system. The losses are calculated before and after the application of TCSC and SVC. The results obtained by applying GWO are validated on IEEE 30-Bus and IEEE 57 bus systems.

It can be concluded that there is a significant reduction in active and reactive power loss after TCSC and SVC being optimized for their size and location by applying GWO.

## 7.2 ATC ENHANCEMENT BY LOCATING FACTS DEVICE USING ACPTDF

Meeting the requirements of an ever-escalating power system, it is very crucial to sustain the competent and cost-effective electricity trades and procedures. With increased power transactions in industrial, commercial, and domestic areas, the system has to supply effectively and reliably while operating near its voltage and thermal limits. This results in the menace of congestion and to resolve this problem the system must be operated optimally to work at its highest capacity reliably without being damaged. Thus, to increase the ATC of the system, TCSC is implemented. The adaptable control capabilities of TCSC to manipulate line reactance under valid transmission limits have been applied to improve the ATC of the standard IEEE 30-Bus system.  Calculation of ATC is carried out for bilateral transactions which in turn is done by applying ACPTDF as a sensitivity factor.  GWO has been applied here to optimally allocate and parameter setting of TCSC. A multi-objective function is formulated to increase ATC and to reduce power losses religiously following the voltage & thermal stability limitations. GWO was found to be more effective and simpler to apply with enhanced efficiency as compared to other optimization methods. Moreover, this optimization method never gets trapped in local minima so is quite consistent and reliable. The results attained for the maximization of ATC for far-end bilateral transactions are more effective than those obtained by FA.

## 7.3 HYBRID PSO-GWO BASED CONGESTION MANAGEMENT

With the incorporation of deregulation in the power industry, the menace of congestion is the most important technical problem faced by the current power system. This chapter introduces a newly developed method for hybrid PSO to GWO algorithm (HPSOGWO) for optimization of TCSC to mitigate congestion. LUF is used here to determine the heavily congested line during contingencies. Optimal placement of TCSC for alleviating congestion is done with the help of a sensitivity factor named DLUF. The optimal size of the TCSC parameter is calculated by using HPSOGWO by solving a multi-objective function. The multi-objective function constitutes the mathematical formulation of enhancement of security margin, voltage deviation reduction, and reduction of system losses. Congestion alleviation is done successfully under various emergency conditions i.e. Line outage, 150% overloading, and 180% overloading. The comparison of the solution of the multi-objective function obtained by HPSOGWO, PSO, and GWO is done. Newly developed HPSOGWO utilized the strengths of GWO and PSO to iterate the complex non-linear system equations and successfully minimized the congestion. The active power loss and voltage deviation are reduced to significant values and the security margin has been brought to the limits to make the system stable. In all the cases HPSOGWO gave superior and improved results as compared to GWO and PSO. HPSOGWO is used for the first time to limit power loss, voltage deviation, and security margin for the mitigation of congestion.

## 7.4 CONGESTION MANAGEMENT BY GENERATOR RESCHEDULING

The chapter proposes a method to merge two very well-proven algorithms PSO and GWO to give a hybrid of two i.e., HPSOGWO. The proposed algorithm is effectively validated on the standard IEEE 30-Bus system. This chapter proposed an effective method to reschedule the generators for their real power output to mitigate congestion. The generators are rescheduled such that the cost of rescheduling is kept at its minimum value, and a way to keep the congestion cost at its minimum value is to reduce the amount of active power rescheduled. All the constraints are satisfied when rescheduling is done. The GSF value of a generator for a congested line is the base to select the suitable generators to participate in the process of rescheduling. The results obtained imply that with the implementation of HPSOGWO, congestion mitigation in the test system is achieved at minimum congestion cost (CC) that too in the least number of iterations. The comparison of results obtained from three methods proves that HPSOGWO outperforms PSO and GWO. This chapter suggests a method to merge PSO with GWO utilizing the strength of the two. PSO is very efficient at initialization while GWO converges very effectively. Thus, here the hybrid of two algorithms is initialized with PSO while convergence is obtained with GWO. PSO has a shortcoming of premature convergence while increased complexity of the system complicates GWO. In the future, more complex systems with higher-level contingencies can be considered with an alternative method to merge the two algorithms.

## 7.5 RE-EVALUATION OF THE METHODS

The transmission test system studied with the line limits, standard voltage values of buses, and total active power loss is minimized concurrently fulfilling all the equality and inequality constraints under consideration. The thorough evaluation and assessments carried out intending to decide the best methodology for the problem specified in the thesis applied to the transmission systems considered, the below-mentioned interpretations and conclusions have been drawn:

1. The congestion mitigation by using LMP and congestion rent methods is effective on small systems, with the increased complexity of the system, these methods become very tedious and the location of TCSC and SVC obtained is not very optimal.
2. The Evolutionary algorithms (PSO, GWO, and FA) require less computation time and give improved results in terms of reduced power transmission limit, suitable voltage profile, and reduced active power loss in the system considered.
3. For the test systems under consideration in this research, comparing all the algorithms (PSO, GWO, and FA), a small difference is realized when the number of iterations, computational times, and precision of all the results are compared. But with a closer look, it is discovered that PSO gives better results than FA. While GWO outperforms both PSO and FA when the number of iterations and precision of solution of the formulated objective function is considered.
4. When the proposed method for merging PSO and GWO is adopted to design a hybrid PSOGWO (HPSOGWO), the convergence characteristics become more suitable for the congested system. Results marked that HPSOGWO has quick convergence and is more precise when congestion cost, rescheduled active power, and minimization of active power loss with a suitable voltage profile is considered.

## 7.6 FUTURE SCOPE

The prime objective of this thesis is the alleviation of the congestion in deregulated power systems by ATC enhancement, active power loss reduction, reduction in voltage deviation, and rescheduling of generators.

1. The same objectives can also be expanded to bilateral and multilateral markets. These markets are nowadays very frequently used in electricity markets in many countries.

2. The research can be further extended to Hybrid pool electricity markets as generator rescheduling is helpful in bilateral as well as hybrid markets.
3. Mitigating congestion, based on the location of the FACTS device can be done by applying multiple advanced FACTS devices.
4. The alleviation of Congestion can also be expanded into financial aspects calculating the threat faced by market participants and their commitment to pay to avert load curtailment.
5. New multi-objective functions can be formulated considering new aspects of the power system.
6. New algorithms can be examined for solving multi-objective functions for congestion management and a comparative analysis of these algorithms can be done.
7. Demand-side management can be implemented with FACTS devices and generator rescheduling to mitigate congestion.

# REFERENCES

[1] *Power sector reform in India*, http:// shodhganga .inflibnet. ac.in /bitstream /10603 /111787/7/chapter- 4.pdf.

[2] Anoop Singh, “Power sector reform in India: Current issues and prospects,” *Energy Policy*, vol. 34, pp. 2480-2490, Sep. 2004.

[3] Anoop Singh, “Towards a competitive market for Electricity and consumer choice in the Indian power sector”, in *Energy Policy*, 2010, vol. 38, pp. 4196-4208.

[4] Yixin Ni, Jin Zhong, and Haoming Liu, “Deregulation of power systems in Asia: special consideration in developing countries”, *IEEE Power Engineering Society General Meeting,* 2005, San Francisco, CA, 2005, pp. 2876-2881 Vol. 3,

[5] A. Papalexopoulos, “Congestion management in a competitive environment”, *PICA 1997 Conference, Tutorial on Future Needs and Trends in Power System Computing,* Columbus, OH, May 1997.

[6] W.W. Hogan, “Nodes and zones in electricity markets: seeking simplified congestion pricing”, *18th Annual North American Conference of the USAEE/IAEE*, San Francisco, California, September 1997.

[7] J. Srinivasa Rao and J. Amamath, “Transmission congestion management comparative studies in restructured power system”, *International Journal of Scientific & Engineering Research (IJSER),* vol. 4(8), pp. 177-182, 2013.

[8] P. Guha Thakurta, D. Van Hertem, and R. Belmans, "An approach for managing switchings of controllable devices in the Benelux to integrate more renewable sources," *IEEE Trondheim PowerTech, Trondheim*, 2011, pp. 1-7.

[9] L.Rajalakshmi, M.V.Suganyadevi and S.Parameswari, “Congestion Management in Deregulated Power System by Locating Series FACTS Devices”, *International Journal of Computer Applications* (0975 – 8887) Volume 13– No.8, January 2011.

[10] C Shekhar and A Kumar, “Congestion Management in Hybrid Electricity Markets with FACTS Devices with Loadability Limits”, *International Journal of Electrical and Computer Engineering*, Vol.2, No. 1, February 2012, pp.75-89.

[11] S. Deb and A. K. Goswami, “Congestion management by generator rescheduling using Artificial Bee Colony Optimization Technique”, *Annual IEEE India Conference (INDICON)*, Kochi, 2012, pp. 909-914,

[12] M. Khanabadi, M. Doostizadeh, A. Esmaeilian, and M. Mohseninezhad, “Transmission congestion management through optimal distributed generation's sizing and placement,” *10th International Conference on Environment and Electrical Engineering*, Rome, 2011, pp. 1-4,

[13] B.V. Manikandan, Raja Charles, P. Venkatesh and M Manasarani., “Comparative Study of Two Congestion Management Methods for the Restructured Power Systems”, *Journal of Electrical Engineering and Technology* 6.10.5370/JEET.2011.6.3.302.

[14] Singh and K. S. Verma, "GA-based congestion management in deregulated power system using FACTS devices," *International Conference & Utility Exhibition on Power and Energy Systems: Issues and Prospects for Asia (ICUE)*, Pattaya City, 2011, pp. 1-6,

[15] Yousefi, A., T.T. Nguyen, H. Zareipour and O.P. Malik, “Congestion management using demand response and FACTS devices.,” *Int. J. Elect. Power Energy Syst.*, 37: 78-85.2011.

[16] R. Ramachandran and P.S. Prakash, “BHA based Optimal Transformer Tap Settings and TCSC Size in Deregulated Power Market for Transmission Congestion”, *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering*, Vol. 6, Issue 3, March 2017

[17] S. Dutta and S. P. Singh, "Optimal Rescheduling of Generators for Congestion Management Based on Particle Swarm Optimization," *IEEE Transactions on Power Systems*, vol. 23, no. 4, pp. 1560-1569, Nov. 2008.

[18] NI, L., Wen, F., and Liu, W., “Congestion management with demand response considering uncertainties of distributed generation outputs and market prices”, in *J. Mod. Power Syst. Clean Energy* 5, 66–78 (2017). https://doi.org/10.1007/s40565-016-0257-9

[19] H.A Gil and G. Joos, “Models for quantifying the economic benefits of distributed generation”, in *IEEE Trans. on Power Syst*. 23(2), 327–335 (2008).

[20] P. Chiradeja and R. Ramakumar, “An approach to quantify the technical benefits of distributed generation”, *IEEE Trans. Power Syst*. 19(4), 764–773 (2004)

[21] R. Ramakumar, “Technology and economic market integration of DG,” *Proc. 2001 Frontiers of Power Conf.*, pp. X 1–X 14.

[22] R. Friedman, “Microturbine power generation: Technology development needs and challenges,” *Environmental Electric Energy Opportunities for the Next Century, IEEE/EPRI Vision-21*, Washington, DC, Apr. 1998.

[23] T Bhattacharjee and A K Chakraborty, “Congestion Management in a Deregulated Power System by Rescheduling of Sensitive Generators and load curtailment using PSO”, *International Journal of Emerging Technology and Advanced Engineering*, ISSN 2250-2459, Volume 2, Issue 3, March 2012.

[24] R. K. Mittapalli and A. Kumar, Y. Pal, and S. Chanana, “Optimal load curtailment in the hybrid electricity market and impact of FACTS,” *2nd International Conference on Power, Control and Embedded Systems*, Allahabad, 2012, pp. 1-7.

[25] Van Hertem D., Eriksson R., Soder L., and Ghandhari M., “Coordination of multiple power flow controlling devices in transmission titles”, *Proceedings of 9th International Conference on AC and DC Transmission*, October 2010, Vol. 9, pp. 6.

[26] R.Ramachandran, M.Arun, and S.Sakthivel, “Optimal Transformer Tap Settings and TCSC Size for Transmission Congestion Management through PSO Algorithm in a Deregulated Power Market,” *International Journal of Scientific & Engineering Research*, Volume 3, Issue 8, August-2012.

[27] S. Shakthivel , D. Priyanga, and S. Sumathi, “Optimal Transformer Tap Settings and TCSC Size for Transmission Congestion management,” *International Journal of Engineering Trends and technology, IJETT*, volume 4, issue 4, April 2013. Page 608.

[28] A. Siddiqui and T. Deb, “Congestion management using FACTS devices”, International *Journal of System Assurance Engineering and Management*. 5. 618-627. 10.1007/s13198-013-0212-3.

[29] A. Kumar , “Congestion Management in Hybrid Electricity Markets with FACTS Devices with Loadability Limits”, *International Journal of Electrical and Computer Engineering (IJECE)*. 2. 10.11591/ijece.v2i1.114.

[30] Brijesh Singh , Ranjit Mahanty, and S.P.Singh, “Optimal Rescheduling of Generators for Congestion Management and Benefit Maximization in a

Decentralized Bilateral Multi-transactions Power Network,” *International Journal of Emerging Electric Power Systems*, Volume 14 Issue 1, May 2013.

[31] A.K. Singh and S.K. Parida, “Congestion management with distributed generation and its impact on electricity market”, *International Journal of Electrical Power & Energy Systems,* Volume 48,2013, Pages 39-47.

[32] Charles Raja, P. Venkatesh, and B. V. Manikandan, "Transmission Congestion Management in restructured power systems," *International Conference on Emerging Trends in Electrical and Computer Technology*, Nagercoil, 2011, pp. 23-28.

[33] S. N. Singh and A. K. David, "Congestion management by optimizing FACTS device location," *International Conference on Electric Utility Deregulation and Restructuring and Power Technologies*. Proceedings (Cat. No.00EX382), London, UK, 2000, pp. 23-28,

[34] K. R. S. Reddy, N. P. Padhy and R. N. Patel, "Congestion management in deregulated power system using FACTS devices," *IEEE Power India Conference*, New Delhi, 2006.

[35] Acharya, Naresh, and N. Mithulananthan. “Locating series FACTS devices for congestion management in deregulated electricity markets”, *Electric Power Systems Research* 77 (2007): 352-360.

[36] M. Gitizadeh and M. Kalantar, “Genetic algorithm-based fuzzy multi-objective approach to congestion management using FACTS devices”, *Electr Eng* 90, 539–549 (2009).

[37] H. Hashemzadeh and S. H. Hosseini, “Locating series FACTS devices using line outage sensitivity factors and particle swarm optimization for congestion management”, *IEEE Power & Energy Society General Meeting, Calgary, AB,* 2009, pp. 1-6,

[38] M. Mandala and C. P. Gupta, “Congestion management by optimal placement of FACTS device”, *Joint International Conference on Power Electronics, Drives and Energy Systems & 2010 Power India*, New Delhi, 2010, pp. 1-7.

[39] N. Anwer, A. S. Siddiqui, and A. Umar, “Analysis of UPFC, SSSC with and without POD in congestion management of transmission system”, *IEEE 5th India International Conference on Power Electronics (IICPE),* Delhi, 2012, pp. 1-6.

[40] Ashwani Kumar and Charan Sekhar, “Congestion management with FACTS devices in deregulated electricity markets ensuring loadability limit”, *International Journal of Electrical Power & Energy Systems,* Volume 46, 2013, Pages 258-273, ISSN 0142-0615.

[41] Siddiqui A.S. and Deb T., “Congestion management using FACTS devices”, *Int Journal of Syst Assur Eng Manag* 5, 618–627 (2014).

[42] J. G. Singh, S. N. Singh, and S. C. Srivastava, “Congestion management by using FACTS controller in power system”, *IEEE Region 10 Humanitarian Technology Conference (R10-HTC),* Agra, 2016, pp. 1-7.

[43] S. K. Gupta, N. K. Yadav, and M. Kumar, “Effect of FACTS Devices on Congestion Management using Active & Reactive Power Rescheduling”, *2nd IEEE International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES),* Delhi, India, 2018, pp. 50-55.

[44] A. A. J. Basha, M. Anitha, and E.B. Elanchezhian, “Optimal placement of TCSC for congestion management in deregulated power system using firefly algorithm”, *International Journal of Process Systems Engineering,* 5(1), 4.

[45] P. Ramasubramanian , G. Uma Prasana and K. Sumath, “Optimal Location of FACTS Devices by Evolutionary Programming Based OPF in Deregulated Power Systems”, *British Journal of Mathematics & Computer Science* 2(1): 21-30, 2012.

[46] Hajforoosh, Somayeh, Nabavi, Seyed Mohammad and Masoum, M.A.S., “Coordinated aggregated-based particle swarm optimization algorithm for congestion management in restructured power market by placement and sizing of the unified power flow controller”, *Science, Measurement & Technology, IET.* 6. 267-278. 10.1049/iet-smt.2011.0143.

[47] Rahmat-Allah Hooshmand, Mohammad Javad Morshed, and Moein Parastegari, “Congestion management by determining the optimal location of series FACTS devices using hybrid bacterial foraging and Nelder–Mead algorithm”, *Applied Soft Computing,* Volume 28,2015, Pages 57-68.

[48] Naraina Avudayappan and S.N. Deepa, “Congestion management in deregulated power system using hybrid cat-firefly algorithm with TCSC and SVC FACTS devices”, *The International Journal for Computation and Mathematics in Electrical and Electronic Engineering,* Vol. 35, Issue 5, September 2016, pp. 1524-1537.

[49] Hadi Besharat and Seyed Abbas Taher, “Congestion management by determining the optimal location of TCSC in deregulated power systems”, *International Journal of Electrical Power & Energy Systems*, Volume 30, Issue 10,2008, Pages 563-568.

[50] Amit Sharma and Ram Avtar Jaswal, “Congestion Management by TCPST In IEEE 9 Bus System Using Matlab Simulink”, *International Journal Of Engineering Sciences & Research Technology*, 2(8): August 2013

[51] Siddiqui, A. S., Khan, S., Ahsan, S., Khan, M. I., and Annamalai, “Application of phase-shifting transformer in Indian Network,” *International Conference on Green Technologies (ICGT).* 2012, pp. 186-191.

[52] K. Roman, O. Robert, and P. Marcin, “Coordination Of Phase Shifting Transformers By Means Of The Swarm Algorithm”, *Elektryka, Zeszyt* 3-4 (243-244), volume 63, 2017.

[53] V. Z. Farahani and A. Kazemi, “Comparing two ways of congestion management in bilateral based power market”, *IEEE GCC Conference (GCC),* Manama, 2006, pp. 1-8.

[54] J. Hazra, A. K. Sinha and Y. Phulpin, “Congestion management using generation rescheduling and/or load shedding of sensitive buses”, *International Conference on Power Systems,* Kharagpur, 2009, pp. 1-5.

[55] M. Houndega , C. M. Muriithi, and C. W. Wekesa, “Active Power Rescheduling for Congestion Management based on generator sensitivity factor using Ant Lion Optimization Algorithm”, *International Journal of Engineering Research and Technology*. ISSN 0974-3154 Volume 11, Number 10 (2018), pp. 1565-1582.

[56] Sujata Balaraman and N Kamaraja, “Transmission congestion management using particle swarm optimization”, *Journal of Electrical Systems,* 7-1 (2011):54 -70.

[57] B. Singh , R. Mahanty , and S. P. Singh, “Optimal Rescheduling of Generators for Congestion Management and Benefit Maximization in a Decentralized Bilateral Multi-Transactions Power Network”, *International Journal of Emerging Electric Power Systems*, volume 14, issue 4.

[58] S. Gope, A. K. Goswami, P. K. Tiwari, and S. Deb, “Generator rescheduling for congestion management using Firefly Algorithm”, *International Conference on Energy Systems and Applications*, Pune, 2015, pp. 40-44.

[59] Md Sarwar and Anwar Shahzad Siddiqui, “An efficient particle swarm optimizer for congestion management in the deregulated electricity market”, *Journal of*

*Electrical Systems and Information Technology*, Volume 2, Issue 3, 2015, Pages 269-282, ISSN 2314-7172.

[60] R. Ramachandran and M. Arun, "Optimal active power rescheduling of generators for congestion management based on sensitivity factors.", *Advances in Natural and Applied Sciences*, vol. 10, no. 15, 2016, p. 13-26. Accessed 18 Nov. 2020.

[61] Sumit Verma and V. Mukherjee, "Firefly algorithm for congestion management in the deregulated environment", *Engineering Science and Technology, an International Journal*, Volume 19, Issue 3, 2016, Pages 1254-1265, ISSN 2215-0986.

[62] Sumit Verma, Subhodip Saha and V. Mukherjee, "Optimal rescheduling of real power generation for congestion management using teaching-learning-based optimization algorithm", *Journal of Electrical Systems and Information Technology,* Volume 5, Issue 3, 2018, Pages 889-907.

[63] S. Sivasankari and N. Chidambararaj, "Generation Rescheduling Based Congestion Management in Restructured Power System", *Middle-East Journal of Scientific Research* 25 (4): 859-863, 2017.

[64] Jagadeeswar Reddy Chintam and Mary Daniel, "Real-Power Rescheduling of Generators for Congestion Management Using a Novel Satin Bowerbird Optimization Algorithm", *Energies*, 11(1), 183. doi:10.3390/en11010183.

[65] Batra I and Ghosh S, "A Novel Approach of Congestion Management in Deregulated Power System Using an Advanced and Intelligently Trained Twin Extremity Chaotic Map Adaptive Particle Swarm Optimization Algorithm", *Arab Journal of Science and Engineering* 44, 6861–6886 (2019).

[66] H. Hedayati, S. A. Nabaviniaki and A. Akbarimajd, "A Method for Placement of DG Units in Distribution Networks", *IEEE Transactions on Power Delivery,* vol. 23, no. 3, pp. 1620-1628, July 2008.

[67] Sudipta Ghosh, S.P. Ghoshal and Saradindu Ghosh, "Optimal sizing and placement of distributed generation in a network system", *International Journal of Electrical Power & Energy Systems,* Volume 32, Issue 8, 2010, Pages 849-856.

[68] S. Porkar, P. Poure, Abbaspour-Tehrani-fard A and S. Saadate, “Optimal allocation of distributed generation using a two-stage multi-objective mixed-integer-nonlinear programming”, *Euro. Trans. Electr. Power,* 21:1072-1087.

[69] M.H. Moradi and M. Abedini, “A combination of genetic algorithm and particle swarm optimization for optimal DG location and sizing in distribution systems”, *International Journal of Electrical Power & Energy Systems*, Volume 34, Issue 1, 2012, Pages 66-74.

[70] A. Ameli ,S. Bahrami , F. Khazaeli and M. R. Haghifam, “A Multiobjective Particle Swarm Optimization for Sizing and Placement of DGs from DG Owner’s and Distribution Company’s Viewpoints”, *IEEE Transactions on Power Delivery*, 29(4), 1831–1840.

[71] Y. Almoataz Abdelaziz, G.H.Yasser,Walid El-Khattam, and M. Othman Mahmoud, “ A Multi-objective Optimization for Sizing and Placement of Voltage-controlled Distributed Generation Using Supervised Big Bang–Big Crunch Method”, *Electric Power Components and Systems*, 43:105–117, 2015

[72] S. J. Hosseini, M. Moradian, H. Shahinzadeh, and S. Ahamadi, “Optimal placement of Distributed Generators with regard to reliability assessment using virus colony search algorithm”, *International Journal of Renewable energy Research,* Vol 8, No. 2 (2018).

[73] Isa A. Mohd, T. Niimura, and R. Yokoyama, “Multicriteria transmission congestion management by load curtailment and generation redispatch in a deregulated power system”, *IEEJ Transactions on Electrical and Electronic Engineering,* 3(5), 524–529.

[74] A. Kashyap and D. Callaway, “Estimating the probability of load curtailment in power systems with responsive distributed storage”, *IEEE 11th International Conference on Probabilistic Methods Applied to Power Systems*, Singapore, 2010, pp. 18-23.

[75] K. Elango and S.R.Paranjothi, “Transmission Congestion Management in Restructured Power System by Generation Rescheduling and Load Shedding using Evolutionary Programming based OPF”, *International Journal of Electrical Engineering.* ISSN 0974-2158 Volume 4, Number 5 (2011), pp. 625-634.

[76] S. S. Reddy, “Multi-Objective Based Congestion Management Using Generation Rescheduling and Load Shedding”, *IEEE Transactions on Power Systems*, vol. 32, no. 2, pp. 852-863, March 2016.

[77] K. Vijayakumar, “Multiobjective Optimization Methods for Congestion Management in Deregulated Power Systems”, Journal of Electrical and Computer Engineering, vol.2012, Article ID 962402, 8 pages, 2012.

[78] S.Visalakshi and S. Baskar, “Multiobjective Decentralized Congestion Management Using Modified NSGA-II”, *Arab J Sci Eng* 36, 827, 2011

[79] S.T. Suganthi , D. Devaraj, T.S. Hosimin, and K. Ramar, “Improved multi-objective differential evolution algorithm for congestion management in restructured power systems”, *IEEE Industrial Electronics and Applications Conference (IEACon).* 2016, pp. 203-210.

[80] Z.K. Fariborz, R. Hadi, and D.M. Hasan, “Multi-objective transmission congestion management considering demand response programs and generation rescheduling”, *Applied Soft Computing*, Volume 70, 2018, Pages 169-181,

[81] S. Surender and K.S. Cheol, “Congestion Management Using Multi-Objective Glowworm Swarm Optimization Algorithm”, *Journal of Electrical Engineering & Technology*. 14. 10.1007/s42835-019-00206-w. , 2019

[82] J C Kaltenbach , J. Peschon , and E. H. Gehrig ,“A mathematical optimization technique for the expansion of electric power transmission systems”, *IEEE Transactions on Power Apparatus and Systems*, (1), pp.113-119.

[83] Momoh J A, *Electric power system applications of optimization*. CRC press.

[84] S. Azim and K.S. Swarup , “Optimal capacitor allocation in radial distribution systems under APDRP”, in *INDICON, 2005 Annual IEEE* (pp. 614-618). IEEE.

[85] A. Seifi and M.R. Hesamzadeh , “A hybrid optimization approach for distribution capacitor allocation considering varying load conditions”, *International Journal of Electrical Power & Energy Systems*, *31*(10), pp.589-595.

[86] M.A.N. Guimaraes, C.A. Castro, and R. Romero, “Distribution systems operation optimization through reconfiguration and capacitor allocation by a dedicated genetic algorithm”, *IET generation, transmission & distribution*, *4*(11), pp.1213-1222.

[87] S.F. Mekhamer , S. A. Soliman , M. A. Moustafa and M.E. El-Hawary, “Application of fuzzy logic for reactive-power compensation of radial distribution feeders”, *IEEE transactions on power systems*, *18*(1), pp.206-213.

[88] A.Y. Abdelaziz, S.F. Mekhamer, and M.H. Nada , "A fuzzy expert system for loss reduction and voltage control in radial distribution systems", *Electric Power Systems Research*, *80*(8), pp.893-897.

[89] K. Prakash and M. Sydulu, "Particle swarm optimization-based capacitor placement on radial distribution systems", *Power Engineering Society General Meeting, 2007. IEEE* (pp. 1-5). IEEE.

[90] I. Ziari , G. Ledwich , A. Ghosh , D. Cornforth and M. Wishart , "Optimal allocation and sizing of capacitors to minimize the transmission line loss and to improve the voltage profile", *Computers & Mathematics with Applications*, *60*(4), pp.1003-1013.

[91] S. P. Singh and A.R. Rao , "Optimal allocation of capacitors in distribution systems using particle swarm optimization", *International Journal of Electrical Power & Energy Systems*, *43*(1), pp.1267-1275.

[92] N.G. Hingorani , L. Gyugyi and M . El-Hawary., *Understanding FACTS: concepts and technology of flexible AC transmission systems* (Vol. 2). New York: IEEE press.

[93] R.J. Shimpi , R.P. Desale , K.S. Patil , J.L. Rajput and S.B.Chavan, "Flexible AC transmission systems", *International Journal of Computer Applications*, *1*(15), pp.54-57. Feb.2010.

[94] X. Luo , J. Wang, M. Dooner and J. Clarke , "Overview of current development in electrical energy storage technologies and the application potential in power system operation", *Applied Energy*, *137*, pp.511-536.

[95] E. Moursi, M.S. and Sharaf, A.M., "Novel reactive power controllers for the STATCOM and SSSC", in *Electric Power Systems Research*, *76*(4), pp.228-241.

[96] P. Kundur , N.J. Balu and M.G. Lauby , Power *system stability and control* (Vol. 7). New York: McGraw-hill.

[97] Ibe O.G. and Onyema A.I., "Concepts of reactive power control and voltage stability methods in power system network", *OSR Journal of Computer Engineering,* 11(2), pp.15-25.

[98] Yao W., Jiang L., Wen J., Wu Q. and Cheng S., "Wide-area damping controller for power system interarea oscillations: A networked predictive control approach", *IEEE Transactions on Control Systems Technology*, *23*(1), pp.27-36.

[99] S.K.S. Abdullah, M.K. Sarmin, N. Saadun ,M.T. Azmi , I.Z. Abidin and I. Musirin, "New generator and shunt reactive power control based secondary

voltage control approach", *International Review of Automatic Control*, *9*(4), pp.192-206.

[100] Le N.A.B.M., Bin W Musa W.M.N., Binti Ismail N., Binti Ishak, N.H. and Binti Salim N.A., "The Modeling of SVC for the Voltage Control in Power System", *Indonesian Journal of Electrical Engineering and Computer Science*, *6*(3).

[101] C.W.Taylor ,G. Scott and A. Hammad, "Static var compensator models for power flow and dynamic performance simulation", *IEEE Transactions on Power Systems (Institute of Electrical and Electronics Engineers) ;(United States)*, *9*(1).

[102] F. Lakdja and F.Z. Gherbi , "Impact of Thyristors Controlled Series Capacitor Devices and Optimal Power Flow on Power Systems", *Leonardo Journal of Sciences, 9*(16), pp.145-157.

[103] N.M.Tabatabaei , G. Aghajani , N.S. Boushehri and S. Shoarinejad ,"Optimal location of FACTS devices using adaptive particle swarm optimization mixed with simulated annealing", *International Journal on Technical and Physical Problems of Engineering (IJTPE), 7,* pp.60-70.

[104] S. Mirjalili , S.M. Mirjalili and A. Lewis , " Grey wolf optimizer", *Advances in Engineering Software*, *69,* pp.46-61.

[105] Y. Wang , P.Yemula and A. Bose , "Decentralized communication and control systems for power system operation", *IEEE Transactions on Smart Grid*, *6*(2), pp.885-893.

[106] K.S. Gupta and H.O. Verma , "Enhancement of Available Transfer Capability by the use of UPFC in Open Power Market", *National Power Systems Conference, NPSC* December 2002.

[107] Ongsakul, Weerakorn, and J. Peerapol, "Optimal allocation of FACTS devices to enhance total transfer capability using evolutionary programming", *IEEE Int symposium on circuits and systems, ISCAS*, vol. 5; 2005. p. 4175–8.

[108] E. Acha , C.R. Fuerte-Esquivel, H. Amirez-Perez , and C. Angeles-Camacho , *FACTS – modelling and simulation in power networks,* John Wiley & Sons*;* 2004.

[109] G. Stephane, C. Rachid, and G. Alain J., "Optimal location of multi-type FACTS devices in a power system by means of genetic algorithms", *IEEE Trans Power Syst* 2001;16(3):537–44.

[110] B.H. Kim , " A study on the convergency property of the auxiliary problem principle", *J ElectrEng Technol* 2006;1(4):455–60.

[111] D. Hur, J.K. Park, and B.H. Kim, “An efficient methodology for security assessment of power systems based on distributed optimal power flow”, *Eur Trans Electr Power* 2003;13(3):161–5.

[112] Ou Y and C. Singh , “Assessment of available transfer capability and margins”, *IEEE Trans Power Syst* 2002;17(2):463–8.

[113] S. Mohamed , Yixin Ni, and F. W. Felix , “Transfer Capability Computations in Deregulated power systems”, *Proceedings of the 33rd Hawaii International Conference on System Sciences,* – 2000.

[114] A. Kumar , S.C. Srivastava , and S.N. Singh , “Available Transfer Capability Assessment in a Competitive Electricity Market Using a Bifurcation Approach”, *IEE Proc. on Generation, Transmission and Distribution, vol.* 151, No. 2, pp. 133 – 140, March 2004.

[115] X. Luo , A.D. Patton , and C.Singh, “Real Power Transfer Capability Calculations Using Multi-Layer Feed Forward Neural Network”, *IEEE Transactions on Power Systems,* 15(2): 903-908, May 2000

[116] Ying-Yi Hong, and Chien-Yang Hsiao, “On-Line ATC estimator using hybrid principal component analysis network”, *Journal of the Chinese Institute of Engineers,* Vol. 30, No. 5, pp. 781-789, 2007.

[117] K. Selvi , N. Ramaraj , and M. Bhavani, “Total Transfer Capability Evaluation using Genetic Algorithms”, *IE(I) Journal – EL,* Vol. 88, pp. 60-64, June 2007.

[118] Y. Xiao, Y. H. Song, and Y. Z. Sun, “Available Transfer Capability Enhancement Using FACTS Devices,”, *Proceedings of the 2000 IEEWPWS Summer Meeting, Seattle,* July 2000, vol. I, pp. 508-515.

[119] L. Gyugyi, Y. H. Song and A. T. Johns, *Flexible AC Transmission Systems (FACTS),* Eds., 1999, Inst. Elect. Eng. Power and Energy Series *30, ch. I.*

[120] M.Venkateswra Rao, S. Sivangaraju, and Chintalapudi V.Suresh, “Available transfer capability evaluation and enhancement using various FACTS controllers: Special focus on system security”, *Ain Shams Engineering Journal,* 2015.

[121] K.S. Bavithra , C. Raja, and P. Venkatesh., “Optimal Setting of FACTS Devices using Particle Swarm Optimization for ATC Enhancement in Deregulated Power System”, *IFAC-Papers on Line* 49.1 (2016): 450-455.

[122] K L Lo, Y S Yuen and L A Snider, “Congestion management in deregulated electricity Markets”, *International Conference on Electrical utility deregulation and restructuring and power technologies,* City University, London, 2000.

[123] A. Kazemi and H. Andami, “FACTS devices in deregulated electric power systems: a review”, *IEEE International Conference on Electric Utility Deregulation, Restructuring and Power Technologies*. Proceedings. ISBN: 0-7803-8237-4,04-10-2004.

[124] Malihe M.Farsang, Hossein Nezamabadi-pour, and Kwang Y.Lee, “Multi-objective VAr Planning with SVC Using Immune Algorithm and Guaranteed Convergence Particle Swarm Optimization”, *IFAC proceedings Volumes*, Volume 41, Issue 2, 2008, Pages 5599-5604

[125] H.I. Shaheen, G.I. Rashed , and S.J. Cheng , “Application of differential evolution algorithm for optimal location and parameters setting of UPFC considering power system security”, *European Transactions on Electrical Power*, 19(7), 911–932.

[126] A. Mohammadi and M. Jazaeri, "A hybrid particle swarm optimization-genetic algorithm for optimal location of svc devices in power system planning," *42nd International Universities Power Engineering Conference*, Brighton, 2007, pp. 1175-1181.

[127] G. Madhusudhana Rao, P. V. Ramarao and T. J. Kumar, “Optimal location of TCSC and SVC for enhancement of ATC in a de-regulated environment using RGA”, *IEEE International Conference on Computational Intelligence and Computing Research*, Coimbatore, 2010, pp. 1-6.

[128] R Agrawal, S.K. Bharadwaj and D.P. Kothari, “Population-based evolutionary optimization techniques for optimal Allocation and sizing of Thyristor Controlled Series Capacitor”, *Journal of electrical systems and information technology*, Volume 5, Issue 3, December 2018, Pages 484-501

[129] A. Rezaee Jordehi, “Brainstorm optimization algorithm (BSOA): An efficient algorithm for finding optimal location and setting of FACTS devices in electric power systems”, *Electrical power and energy systems* 69(2015) 48-57

[130] I Khan, M.A. Mallick, M. Rafi, and M. S. Mirza, “Optimal placement of FACTS controller scheme for enhancement of power system security in Indian scenario”, *Journal of Electrical Systems and Information Technology*, Volume 2, Issue 2, September 2015, Pages 161-171.

[131] M. Mandala and C. P. Gupta, "Optimal Placement of TCSC for Transmission Congestion Management Using Hybrid Optimization Approach", *International Conference on IT Convergence and Security (ICITCS)*, 23-2014, Macao, China.

[132] M.V, Rao, S.Sivanagarajub, and C. V.Suresh, “Available transfer capability evaluation and enhancement using various FACTS controllers: Special focus on system security”, *Ain Shams Engineering Journal,* Volume 7, Issue 1, March 2016, Pages 191-207

[133] M. Esmaili, H.Ali Shayanfar and R. Moslemi, "Locating series FACTS devices for multi-objective congestion management improving voltage and transient stability”, *European Journal of Operational Research,* Volume 236, Issue 2, 16 July 2014, Pages 763-773.

[134] A. S. Siddiqui, Mohd T. Khan, and F. Iqbal, “Determination of optimal location of TCSC and STATCOM for congestion management in deregulated power system”, *International Journal of System Assurance Engineering Management,* 10.1007/s13198-014-0332-4

[135] P. Choudekar , S. Sinha, and A. Siddiqui , “Optimal placement of thyristor controlled series compensators for mitigation of congestion under critical contingency condition”, *CSI Transactions on ICT*, 4(2-4), 259–264.

[136] Y. Manganuri, P. Choudekar, Abhishek, D. Asija and Ruchira, "Optimal location of TCSC using sensitivity and stability indices for reduction in losses and improving the voltage profile," *2016 IEEE 1st International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES),* Delhi, 2016, pp. 1-4.

[137] A. Mishra and G V Nagesh Kr, “Congestion management of deregulated power systems by the optimal setting of Interline Power Flow Controller using Gravitational Search algorithm”, *Journal of Electrical Systems and Information Technology,* Volume 4, Issue 1, May 2017, Pages 198-212.

[138] M. Gupta, V. Kumar, G. K. Banerjee, and N. K. Sharma, “ Mitigating Congestion in a Power System and Role of FACTS Devices”, *Advances in Electrical Engineering* , Volume 2017, pp1-7.

[139] A. Sharma and S. K Jain, “Gravitational search assisted algorithm for TCSC placement for congestion control in deregulated power system”, *Electrical power system research,* Volume 174, September 2019, 105874

[140] J. Kennedy, R. Eberhart ,“Particle Swarm Optimization”, *Proceedings of IEEE International Conference on Neural Networks.* IV. pp. 1942–1948.

[141] G. Yesuratnam and T. Dhadbanjan , "Congestion management in open access based on relative electrical distance using voltage stability criteria", *Electric Power Systems Research*. 77. 1608-1618. 10.1016/j.epsr.2006.11.007.

[142] E. Shayesteh , M. P. Moghaddam , S. Taherynejhad and M. K Sheikh-EL-Eslami, "Congestion Management using Demand Response programs in power market", *IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century,* Pittsburgh, PA, pp. 1-8.

[143] J. Hazra , A. K. Sinha and Y. Phulpin , "Congestion management using generation rescheduling and/or load shedding of sensitive buses", *International Conference on Power Systems,* Kharagpur, pp. 1-5.

[144] N.I. Yusoff , A. Zin A. M. and A. B. Khairuddin, "Congestion management in power system: A review", *3rd International Conference on Power Generation Systems and Renewable Energy Technologies (PGSRET),* Johor Bahru, pp. 22-27.

[145] P. Boonyaritdachochai, C. Boonchuay , and W Ongsakul, "Optimal congestion management in an electricity market using particle swarm optimization with time-varying acceleration coefficients", *Computers & Mathematics with Applications,* Volume 60, Issue 4, Pages 1068-1077.

[146] U. Romero , M.C. Edgar Franco, and M. Rashidinejad , "Applications of Heuristics and Metaheuristics in Power Systems", *Journal of Electrical and Computer Engineering,* Article 658507, 2 pages.

[147] B.K. Panigrahi and V.P. Ravikumar , "Congestion management using adaptive bacterial foraging algorithm", *Energy Conversion and Management*, Volume 50, Issue 5, Pages1202-1209.

[148] C.H. Venkaiah and D.M. Vinod Kumar, "Fuzzy adaptive bacterial foraging congestion management using sensitivity-based optimal active power re-scheduling of generators", *Applied Soft Computing,* Volume 11, Issue 8, Pages 4921-4930.

[149] K. Vijayakumar and R. Jegatheesan, "Optimal Location and Sizing of DG for Congestion Management in Deregulated Power Systems in: Swarm, Evolutionary, and Memetic Computing", *SEMCCO 2012. Lecture Notes in Computer Science,* vol 7677.

[150] J.R. Preetha , D. Devaraj , and S. D. Sekhar , “Multi-Objective Genetic Algorithm for voltage stability enhancement using rescheduling and FACTS devices”, *Ain Shams Engineering Journal*, Volume 5, Issue 3, 2014, Pages 789-801.

[151] S. Sivakumar and D. Devaraj, “Congestion management in deregulated power system by rescheduling of generators using genetic algorithm”, *International Conference on Power Signals Control and Computations (EPSCICON),* Thrissur, pp. 1-5.

[152] M.Sarwar and A.S. Siddiqui, “An efficient particle swarm optimizer for congestion management in deregulated electricity market”, *Journal of Electrical Systems and Information Technology*, Volume 2, Issue 3, Pages 269-282.

[153] S. Verma and V. Mukherjee, “Firefly algorithm for congestion management in deregulated environment”, *Engineering Science and Technology, an International Journal*, Volume 19, Issue 3, Pages 1254-1265.

[154] S. K. Behera and N.K. Mohanty, “A FIS-GA combined approach for transmission congestion management in restructured power system”, *International Journal of Mathematical Modelling and Numerical Optimisation (IJMMNO),* Vol. 7, No. 3/4.

[155] M. Houndjega , C.M. Muriithi , and C.W. Wekesa ,” Active Power Rescheduling for Congestion Management based on generator sensitivity factor using Ant Lion Optimization Algorithm”, *International Journal of Engineering Research and Technology.* ISSN 0974-3154 Volume 11, Number 10 pp. 1565-1582.

[156] A. Eladl , S. Kaddah and E. Haikal, “Optimal generation rescheduling for congestion management, LMP enhancement and social welfare maximization”, *Nineteenth International Middle East Power Systems Conference (MEPCON),* Cairo, pp. 1190-1194.

[157] R. Eberhart and J. Kennedy, “A new optimizer using particle swarm theory”, *MHS'95. Proceedings of the Sixth International Symposium on Micro Machine and Human Science,* Nagoya, Japan, pp. 39-43, doi: 10.1109/MHS.1995.494215.

[158] S. Deb , S. Gope , and A. K. Goswami, “Generator rescheduling for congestion management with incorporation of wind farm using Artificial Bee Colony algorithm”, *Annual IEEE India Conference (INDICON),* Mumbai, 2013, pp. 1-6.

[159] I. Totonchi , H.A. Akash , A.A. Akash and A. Faza, “Sensitivity analysis for the IEEE 30-Bus system using load-flow studies”, *3rd International Conference on Electric Power and Energy Conversion Systems,* Istanbul, pp. 1-6.

# APPENDICES

## APPENDIX-A

### IEEE 30-Bus System Data

Figure A.1 shows the single line diagram of standard IEEE 30-bus system.

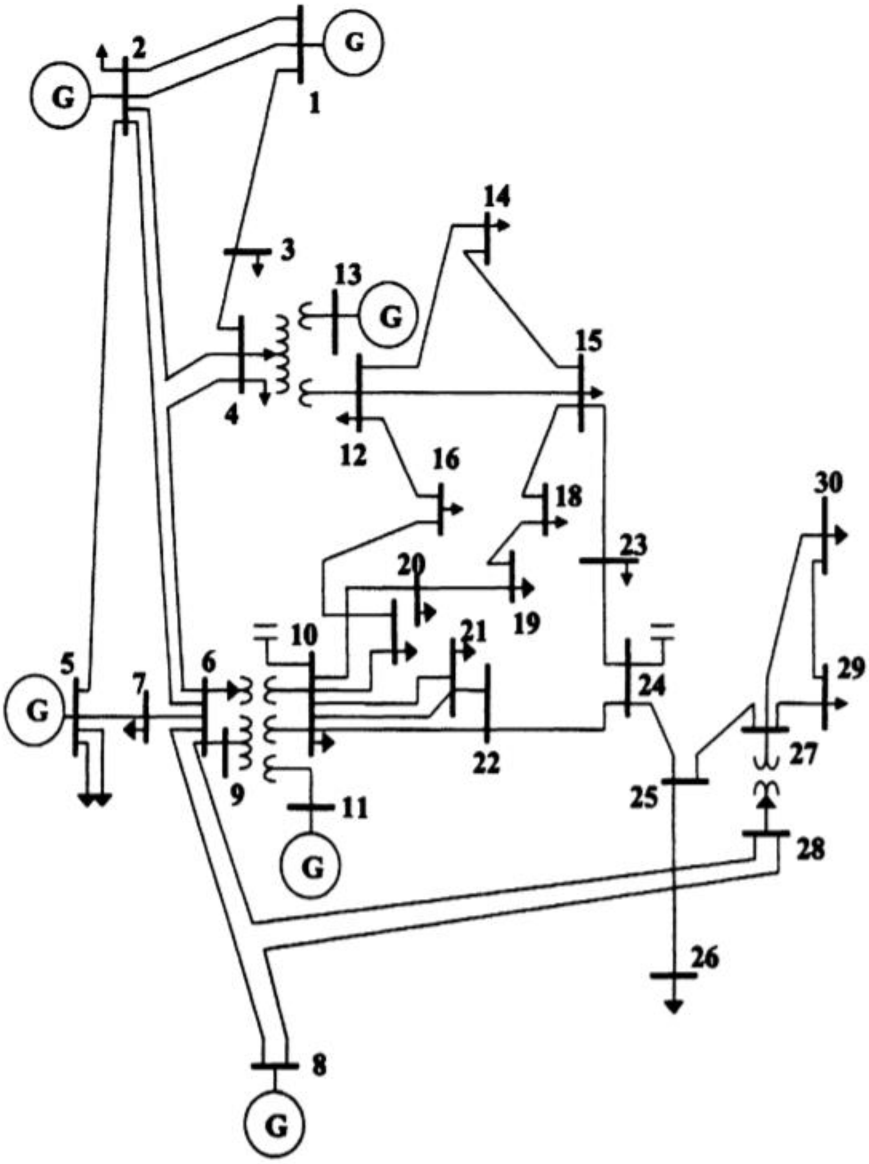

Figure A.1: Single line diagram of standard IEEE 30-Bus system

The Load bus data, transmission line data, modified generating units’ coefficients with ramp rate limits data, generator cost and emission coefficients data and shunt capacitance data are provided in Table A.1, Table A.2, Table A.3, Table A.4 and Table A.5. This system constitutes 30-bus with 41 interconnected lines. All data is on 100 MVA base. For the data to be used for power system analysis $V_i^{min}$, $V_i^{max}$, $\emptyset_i^{max}$ and $\emptyset_i^{min}$ are considered equal to 0.9p.u., 1.1p.u., -45 degrees and +45 degrees respectively.

**Table A.1. Load bus DATA**

| Bus No | Load | | Bus No | Load | |
|---|---|---|---|---|---|
| | P (MW) | Q (MVAr) | | P (MW) | Q (MVAr) |
| 1 | 0.00 | 0.00 | 16 | 3.50 | 1.80 |
| 2 | 21.7 | 12.7 | 17 | 9.00 | 5.80 |
| 3 | 2.40 | 1.20 | 18 | 3.20 | 0.90 |
| 4 | 7.60 | 1.60 | 19 | 9.50 | 3.40 |
| 5 | 94.2 | 19.0 | 20 | 2.20 | 0.70 |
| 6 | 0.00 | 0.00 | 21 | 17.5 | 11.2 |
| 7 | 22.8 | 10.9 | 22 | 0.00 | 0.00 |
| 8 | 30.0 | 30.0 | 23 | 3.20 | 1.60 |
| 9 | 0.00 | 0.00 | 24 | 8.70 | 6.70 |
| 10 | 5.80 | 2.00 | 25 | 0.00 | 0.00 |
| 11 | 0.00 | 0.00 | 26 | 3.50 | 2.30 |
| 12 | 11.2 | 7.50 | 27 | 0.00 | 0.00 |
| 13 | 0.00 | 0.00 | 28 | 0.00 | 0.00 |
| 14 | 6.20 | 1.60 | 29 | 2.40 | 0.90 |
| 15 | 8.20 | 2.50 | 30 | 10.6 | 1.90 |

**Table A.2 Transmission Line Data**

| Line No. | From Bus | To Bus | Series Impedance (p.u.) | | Half Line Charging susceptance (p.u.) | Tap Setting | MVA Rating | Annual Cost (K$/year) |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 2 | 0.01920 | 0.05750 | 0.02640 | - | 130 | 216.6125 |
| 2 | 1 | 3 | 0.04520 | 0.18520 | 0.02040 | - | 130 | 307.2875 |
| 3 | 2 | 4 | 0.05700 | 0.17370 | 0.01840 | - | 65 | 509.9500 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 4 | 3 | 4 | 0.01320 | 0.03790 | 0.00420 | - | 130 | 700.0000 |
| 5 | 2 | 5 | 0.04720 | 0.19830 | 0.02090 | - | 130 | 721.5250 |
| 6 | 2 | 6 | 0.05810 | 0.17630 | 0.01870 | - | 65 | 168.1750 |
| 7 | 4 | 6 | 0.01190 | 0.04140 | 0.00450 | - | 90 | 474.3000 |
| 8 | 5 | 7 | 0.04600 | 0.11600 | 0.01020 | - | 70 | 62.0000 |
| 9 | 6 | 7 | 0.02670 | 0.08200 | 0.00850 | - | 130 | 130.2000 |
| 10 | 6 | 8 | 0.01200 | 0.04200 | 0.00450 | - | 32 | 104.6250 |
| 11 | 6 | 9 | 0.00000 | 0.20800 | 0.00000 | 1.0155 | 65 | 306.9000 |
| 12 | 6 | 10 | 0.00000 | 0.55600 | 0.00000 | 0.9629 | 32 | 20.9250 |
| 13 | 9 | 11 | 0.00000 | 0.20800 | 0.00000 | - | 65 | 83.7000 |
| 14 | 9 | 10 | 0.00000 | 0.11000 | 0.00000 | - | 65 | 927.6750 |
| 15 | 4 | 12 | 0.00000 | 0.25600 | 0.00000 | 1.0129 | 65 | 554.1250 |
| 16 | 12 | 13 | 0.00000 | 0.14000 | 0.00000 | - | 65 | 15.1125 |
| 17 | 12 | 14 | 0.12310 | 0.25590 | 0.00000 | - | 32 | 30.2250 |
| 18 | 12 | 15 | 0.06620 | 0.13040 | 0.00000 | - | 32 | 97.6500 |
| 19 | 12 | 16 | 0.09450 | 0.19870 | 0.00000 | - | 32 | 179.0250 |
| 20 | 14 | 15 | 0.2210 | 0.19970 | 0.00000 | - | 16 | 124.7750 |
| 21 | 16 | 17 | 0.08240 | 0.19320 | 0.00000 | - | 16 | 146.4750 |
| 22 | 15 | 18 | 0.10700 | 0.21850 | 0.00000 | - | 16 | 80.6000 |
| 23 | 18 | 19 | 0.06390 | 0.12920 | 0.00000 | - | 16 | 235.6000 |
| 24 | 19 | 20 | 0.03400 | 0.06800 | 0.00000 | - | 32 | 186.0000 |
| 25 | 10 | 20 | 0.09360 | 0.20900 | 0.00000 | - | 32 | 117.8000 |
| 26 | 10 | 17 | 0.03240 | 0.08450 | 0.00000 | - | 32 | 167.4000 |
| 27 | 10 | 21 | 0.03480 | 0.07490 | 0.00000 | - | 32 | 160.4250 |
| 28 | 10 | 22 | 0.07270 | 0.14990 | 0.00000 | - | 32 | 195.3000 |
| 29 | 21 | 22 | 0.01160 | 0.02360 | 0.00000 | - | 32 | 166.2375 |
| 30 | 15 | 23 | 0.10000 | 0.20200 | 0.00000 | - | 16 | 100.7500 |
| 31 | 22 | 24 | 0.11500 | 0.17900 | 0.00000 | - | 16 | 40.3000 |
| 32 | 23 | 24 | 0.13200 | 0.27000 | 0.00000 | - | 16 | 65.1000 |
| 33 | 24 | 25 | 0.18850 | 0.32920 | 0.00000 | - | 16 | 210.8000 |
| 34 | 25 | 26 | 0.25440 | 0.38000 | 0.00000 | - | 16 | 204.6000 |
| 35 | 25 | 27 | 0.10930 | 0.20870 | 0.00000 | - | 16 | 83.7000 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 36 | 28 | 27 | 0.00000 | 0.36900 | 0.00000 | 0.9581 | 65 | 223.2000 |
| 37 | 27 | 29 | 0.21980 | 0.41530 | 0.00000 | - | 16 | 160.4250 |
| 38 | 27 | 30 | 0.32020 | 0.60270 | 0.00000 | - | 16 | 90.6750 |
| 39 | 29 | 30 | 0.23990 | 0.45330 | 0.00000 | - | 16 | 216.6125 |
| 40 | 8 | 28 | 0.06360 | 0.20000 | 0.02140 | - | 32 | 54.2500 |
| 41 | 6 | 28 | 0.01690 | 0.00650 | 0.00650 | - | 32 | 210.8000 |

**Table A.3 Modified Generating units' coefficients with Ramp rate limits**

| Gen. No. | $P_{gi}^{min}$ | $P_{gi}^{max}$ | $a_i$ | $b_i$ | $c_i$ | $d_i$ | $e_i$ | K | $P_{gi}^{0}$ | $UR_i$ | $DR_i$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 50 | 63.75 | 0 | 3.06 | 87.5 | 0 | 0 | 0 | 135 | 65 | 85 |
| | 63.750 | 82.87 | 0 | 0.00 | 0.0 | 0 | 0 | 282 | | | |
| | 82.875 | 93.75 | 0 | 8.92 | -457 | 0 | 0 | 0 | | | |
| | 93.750 | 157.5 | 0 | 3.70 | 32 | 0 | 0 | 0 | | | |
| | 157.50 | 176.6 | 0 | 0.000 | 0 | 0 | 0 | 615 | | | |
| | 176.625 | 200 | 0 | 7.700 | -745 | 0 | 0 | 0 | | | |
| 2 | 25 | 43 | 0.010 | 0.300 | 35 | 0 | 0 | 0 | 65 | 12 | 22 |
| | 43 | 63 | 0.020 | 0.600 | 60 | 0 | 0 | 0 | | | |
| 3 | 20 | 49 | 0.070 | 0.095 | 45 | 40 | 0.08 | 0 | 35 | 12 | 15 |
| 4 | 15 | 30 | 0.090 | 0.025 | 30 | 30 | 0.09 | 0 | 25 | 8 | 16 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 5 | 13 | 28 | 0.025 | 3.000 | 0 | 0 | 0 | 0 | 20 | 06 | 09 |
| 6 | 14 | 35 | 0.025 | 3.000 | 0 | 0 | 0 | 0 | 30 | 08 | 16 |

**Table A.4. Generator Cost and Emission Coefficients**

| **Gen. No.** | $P_i^{min}$ **(MW)** | $P_i^{max}$ **(MW)** | $Q_i^{min}$ **(MVAr)** | $Q_i^{max}$ **(MVAr)** | $a_i$ | $b_i$ | $c_i$ | $\alpha_i$ | $\beta_i$ | $\gamma_i$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 50 | 200 | - | - | 0.003 | 2.00 | 0 | 0.012 | -0.101 | 22.98 |
| 2 | 20 | 80 | -20 | 100 | 0.017 | 1.75 | 0 | 0.020 | -0.100 | 25.31 |
| 3 | 15 | 50 | -15 | 80 | 0.062 | 1.00 | 0 | 0.027 | -0.010 | 25.50 |
| 4 | 10 | 35 | -15 | 60 | 0.008 | 3.25 | 0 | 0.029 | -0.005 | 24.90 |
| 5 | 10 | 30 | -10 | 50 | 0.025 | 3.00 | 0 | 0.029 | -0.004 | 24.70 |
| 6 | 12 | 40 | -15 | 60 | 0.025 | 3.00 | 0 | 0.027 | -0.005 | 25.30 |

**Table A.5. Shunt Capacitor Data**

| **Bus No.** | **Susceptance** |
|---|---|
| 10 | 19 |
| 24 | 4 |

**Table A.5. Generator bidding co-efficients for IEEE 30 bus test system**

| | **Bids Submitted by Generators in $/MWhr** | |
|---|---|---|
| **Generator Bus Number** | **R(upward)** | **R(downward)** |
| 1 | 15 | 11 |
| 2 | 17 | 8 |
| 5 | 19 | 8 |
| 8 | 20 | 12 |
| 11 | 15 | 10 |
| 13 | 10 | 5 |

# APPENDIX-B

## IEEE 57-Bus System Data

Figure B.1 presents the single line diagram of standard IEEE 57-Bus system.

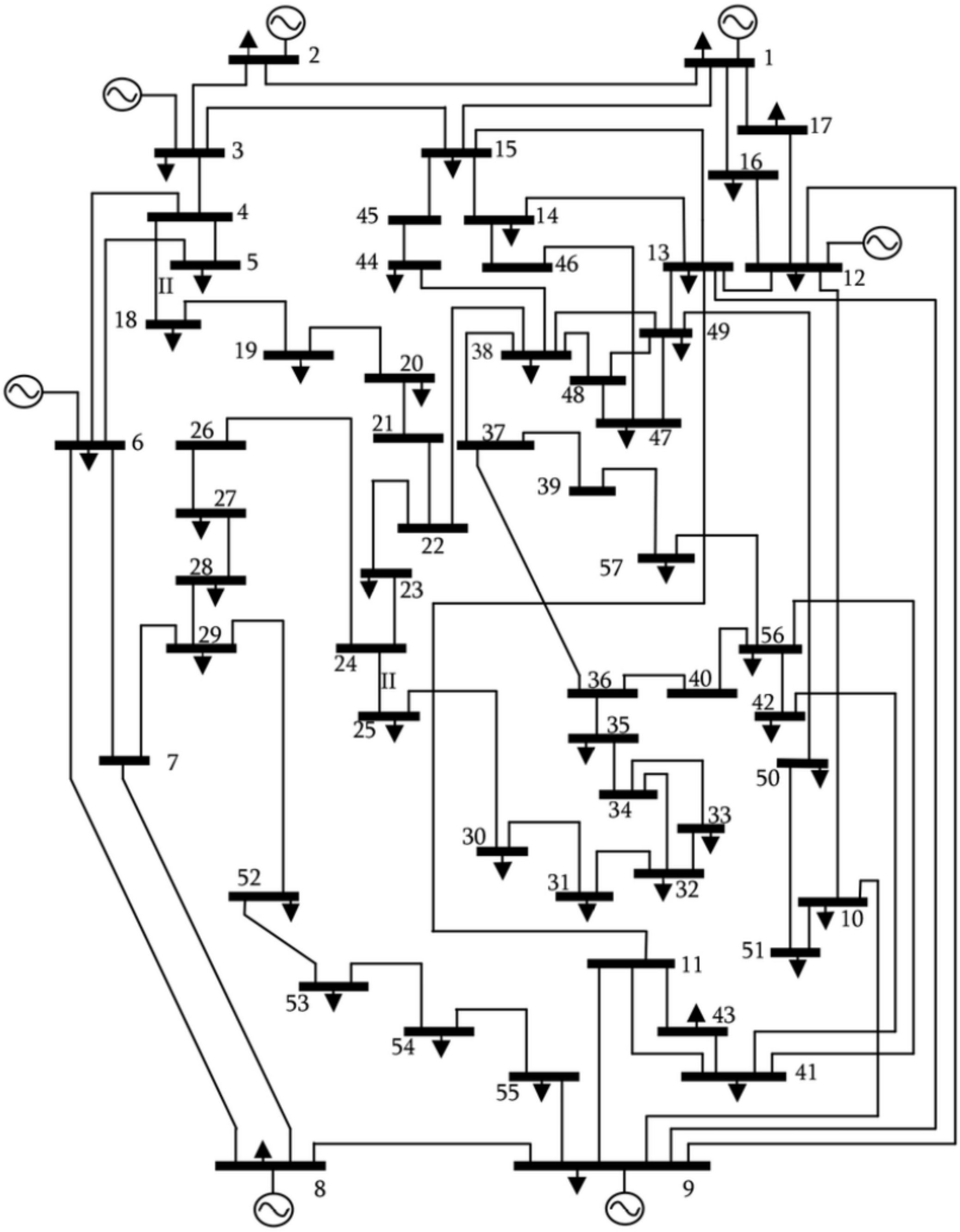

**Figure B.1. Single line diagram of standard IEEE 57 bus system**

IEEE 57 bus system comprises of 7 generators, 57 buses, 17 transformers and 63 lines. This test system is classified into three areas with rated voltage as 69kV, 18 kV and 13.8 kV. 100 MVA is taken as base MVA for the test system. Line data, Bus data, transformer tap setting values and capacitor data are shown in Table B.1, B.2, B.3 and B.4.

**Table B.1. Line Data**

| Line No. | From Bus | To Bus | Line Impedance | | Half Line Charging Susceptance |
|---|---|---|---|---|---|
| 1 | 1 | 2 | 0.0083 | 0.028 | 0.0645 |
| 2 | 2 | 3 | 0.0298 | 0.058 | 0.0409 |
| 3 | 3 | 4 | 0.0112 | 0.0366 | 0.0190 |
| 4 | 4 | 5 | 0.0625 | 0.132 | 0.0129 |
| 5 | 4 | 6 | 0.043 | 0.148 | 0.0174 |
| 6 | 6 | 7 | 0.02 | 0.102 | 0.0138 |
| 7 | 6 | 8 | 0.0339 | 0.173 | 0.0235 |
| 8 | 8 | 9 | 0.0099 | 0.0505 | 0.0274 |
| 9 | 9 | 10 | 0.0369 | 0.1679 | 0.0220 |
| 10 | 9 | 11 | 0.0258 | 0.0848 | 0.0109 |
| 11 | 9 | 12 | 0.0648 | 0.295 | 0.0386 |
| 12 | 9 | 13 | 0.0481 | 0.158 | 0.0203 |
| 13 | 13 | 14 | 0.0132 | 0.0434 | 0.0055 |
| 14 | 13 | 15 | 0.0269 | 0.0869 | 0.0115 |
| 15 | 1 | 15 | 0.0178 | 0.091 | 0.0494 |
| 16 | 1 | 16 | 0.0454 | 0.260 | 0.0273 |
| 17 | 1 | 17 | 0.0238 | 0.108 | 0.0143 |
| 18 | 3 | 15 | 0.0162 | 0.053 | 0.0272 |
| 19 | 4 | 18 | 0 | 0.555 | 0 |
| 20 | 4 | 18 | 0 | 0.43 | 0 |
| 21 | 5 | 6 | 0.0302 | 0.0641 | 0.0062 |
| 22 | 7 | 8 | 0.0139 | 0.0712 | 0.0097 |
| 23 | 10 | 12 | 0.0277 | 0.1262 | 0.0164 |

| | | | | | |
|---|---|---|---|---|---|
| 24 | 11 | 13 | 0.0223 | 0.0732 | 0.0094 |
| 25 | 12 | 13 | 0.0178 | 0.058 | 0.0302 |
| 26 | 12 | 16 | 0.018 | 0.0813 | 0.0108 |
| 27 | 12 | 17 | 0.0397 | 0.179 | 0.0238 |
| 28 | 14 | 15 | 0.0171 | 0.0547 | 0.0074 |
| 29 | 18 | 19 | 0.461 | 0.685 | 0 |
| 30 | 19 | 20 | 0.283 | 0.434 | 0 |
| 31 | 21 | 20 | 0 | 0.7767 | 0 |
| 32 | 21 | 22 | 0.0736 | 0.117 | 0 |
| 33 | 22 | 23 | 0.0099 | 0.0152 | 0 |
| 34 | 23 | 24 | 0.166 | 0.256 | 0.0042 |
| 35 | 24 | 25 | 0 | 1.182 | 0 |
| 36 | 24 | 25 | 0 | 1.23 | 0 |
| 37 | 24 | 26 | 0 | 0.0473 | 0 |
| 38 | 26 | 27 | 0.165 | 0.254 | 0 |
| 39 | 27 | 28 | 0.0618 | 0.0954 | 0 |
| 40 | 28 | 29 | 0.0418 | 0.0587 | 0 |
| 41 | 7 | 29 | 0 | 0.0648 | 0 |
| 42 | 25 | 30 | 0.135 | 0.202 | 0 |
| 43 | 30 | 31 | 0.326 | 0.497 | 0 |
| 44 | 31 | 32 | 0.507 | 0.755 | 0 |
| 45 | 32 | 33 | 0.0392 | 0.036 | 0 |
| 46 | 34 | 32 | 0 | 0.953 | 0 |
| 47 | 34 | 35 | 0.052 | 0.078 | 0.0016 |
| 48 | 35 | 36 | 0.043 | 0.0537 | 0.0008 |
| 49 | 36 | 37 | 0.029 | 0.0366 | 0 |
| 50 | 37 | 38 | 0.0651 | 0.1009 | 0.0010 |
| 51 | 37 | 39 | 0.0239 | 0.0379 | 0 |
| 52 | 36 | 40 | 0.03 | 0.0466 | 0 |
| 53 | 22 | 38 | 0.0192 | 0.0295 | 0 |
| 54 | 11 | 41 | 0 | 0.749 | 0 |
| 55 | 41 | 42 | 0.207 | 0.352 | 0 |

| | | | | | |
|---|---|---|---|---|---|
| 56 | 41 | 43 | 0 | 0.412 | 0 |
| 57 | 38 | 44 | 0.02289 | 0.0585 | 0.0010 |
| 58 | 15 | 45 | 0 | 0.1042 | 0 |
| 59 | 14 | 46 | 0 | 0.0735 | 0 |
| 60 | 46 | 47 | 0.023 | 0.068 | 0.0016 |
| 61 | 47 | 48 | 0.0182 | 0.0233 | 0 |
| 62 | 48 | 49 | 0.0834 | 0.129 | 0.0024 |
| 63 | 49 | 50 | 0.0801 | 0.128 | 0 |
| 64 | 50 | 51 | 0.1386 | 0.22 | 0 |
| 65 | 10 | 51 | 0 | 0.0712 | 0 |
| 66 | 13 | 49 | 0 | 0.191 | 0 |
| 67 | 29 | 52 | 0.1442 | 0.187 | 0 |
| 68 | 52 | 53 | 0.0762 | 0.0984 | 0 |
| 69 | 53 | 54 | 0.1878 | 0.232 | 0 |
| 70 | 54 | 55 | 0.1732 | 0.2265 | 0 |
| 71 | 11 | 43 | 0 | 0.153 | 0 |
| 72 | 44 | 45 | 0.0624 | 0.1242 | 0.0020 |
| 73 | 40 | 56 | 0 | 1.195 | 0 |
| 74 | 56 | 41 | 0.553 | 0.549 | 0 |
| 75 | 56 | 42 | 0.2125 | 0.354 | 0 |
| 76 | 39 | 57 | 0 | 1.355 | 0 |
| 77 | 57 | 56 | 0.174 | 0.26 | 0 |
| 78 | 38 | 49 | 0.115 | 0.177 | 0.0030 |
| 79 | 38 | 48 | 0.0312 | 0.0482 | 0 |
| 80 | 9 | 55 | 0 | 0.1205 | 0 |

**Table B.2. Bus Data**

| **Bus no.** | **Bus Voltage** | | **Generation** | | **Load** | | **Reactive power** | |
|---|---|---|---|---|---|---|---|---|
| | **Magnitude (p.u.)** | **Phase Angle (degrees)** | **Real Power (p.u.)** | **Reactive Power (p.u.)** | **Real Power (p.u.)** | **Reactive Power (p.u.)** | **$Q_{min}$ (p.u.)** | **$Q_{max}$ (p.u.)** |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 1 | 1.040 | 0.000 | 4.78 | 1.289 | 0.55 | 0.17 | - | - |
| 2 | 1.010 | 0.000 | 0.000 | -0.008 | 0.03 | 0.88 | -0.17 | 0.50 |
| 3 | 0.985 | 0.000 | 0.4 | -0.01 | 0.41 | 0.21 | -0.10 | 0.60 |
| 4 | 1.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | - | - |
| 5 | 1.000 | 0.000 | 0.000 | 0.000 | 0.13 | 0.04 | - | - |
| 6 | 0.98 | 0.000 | 0.000 | 0.008 | 0.75 | 0.02 | -0.08 | 0.25 |
| 7 | 1.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | - | - |
| 8 | 1.005 | 0.000 | 4.50 | 0.621 | 1.50 | 0.22 | -1.40 | 2 |
| 9 | 0.98 | 0.000 | 0.000 | 0.022 | 1.21 | 0.26 | -0.03 | 0.09 |
| 10 | 1.000 | 0.000 | 0.000 | 0.000 | 0.05 | 0.02 | - | - |
| 11 | 1.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | - | - |
| 12 | 1.015 | 0.000 | 3.10 | 1.285 | 3.77 | 0.24 | -0.5 | 1.55 |
| 13 | 1.000 | 0.000 | 0.000 | 0.000 | 0.18 | 0.023 | - | - |
| 14 | 1.000 | 0.000 | 0.000 | 0.000 | 0.105 | 0.053 | - | - |
| 15 | 1.000 | 0.000 | 0.000 | 0.000 | 0.22 | 0.05 | - | - |
| 16 | 1.000 | 0.000 | 0.000 | 0.000 | 0.43 | 0.03 | - | - |
| 17 | 1.000 | 0.000 | 0.000 | 0.000 | 0.42 | 0.08 | - | - |
| 18 | 1.000 | 0.000 | 0.000 | 0.000 | 0.272 | 0.098 | - | - |
| 19 | 1.000 | 0.000 | 0.000 | 0.000 | 0.033 | 0.06 | - | - |
| 20 | 1.000 | 0.000 | 0.000 | 0.000 | 0.023 | 0.01 | - | - |
| 21 | 1.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | - | - |
| 22 | 1.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | - | - |
| 23 | 1.000 | 0.000 | 0.000 | 0.000 | 0.063 | 0.021 | - | - |
| 24 | 1.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | - | - |
| 25 | 1.000 | 0.000 | 0.000 | 0.000 | 0.063 | 0.032 | - | - |
| 26 | 1.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | - | - |
| 27 | 1.000 | 0.000 | 0.000 | 0.000 | 0.093 | 0.005 | - | - |
| 28 | 1.000 | 0.000 | 0.000 | 0.000 | 0.046 | 0.023 | - | - |
| 29 | 1.000 | 0.000 | 0.000 | 0.000 | 0.17 | 0.026 | - | - |
| 30 | 1.000 | 0.000 | 0.000 | 0.000 | 0.036 | 0.018 | - | - |
| 31 | 1.000 | 0.000 | 0.000 | 0.000 | 0.058 | 0.029 | - | - |
| 32 | 1.000 | 0.000 | 0.000 | 0.000 | 0.016 | 0.008 | - | - |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 33 | 1.000 | 0.000 | 0.000 | 0.000 | 0.038 | 0.019 | - | - |
| 34 | 1.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | - | - |
| 35 | 1.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | - | - |
| 36 | 1.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | - | - |
| 37 | 1.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | - | - |
| 38 | 1.000 | 0.000 | 0.000 | 0.000 | 0.14 | 0.07 | - | - |
| 39 | 1.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | - | - |
| 40 | 1.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | - | - |
| 41 | 1.000 | 0.000 | 0.000 | 0.000 | 0.063 | 0.03 | - | - |
| 42 | 1.000 | 0.000 | 0.000 | 0.000 | 0.071 | 0.044 | - | - |
| 43 | 1.000 | 0.000 | 0.000 | 0.000 | 0.02 | 0.01 | - | - |
| 44 | 1.000 | 0.000 | 0.000 | 0.000 | 0.12 | 0.018 | - | - |
| 45 | 1.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | - | - |
| 46 | 1.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | - | - |
| 47 | 1.000 | 0.000 | 0.000 | 0.000 | 0.297 | 0.116 | - | - |
| 48 | 1.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | - | - |
| 49 | 1.000 | 0.000 | 0.000 | 0.000 | 0.18 | 0.085 | - | - |
| 50 | 1.000 | 0.000 | 0.000 | 0.000 | 0.21 | 0.105 | - | - |
| 51 | 1.000 | 0.000 | 0.000 | 0.000 | 0.18 | 0.053 | - | - |
| 52 | 1.000 | 0.000 | 0.000 | 0.000 | 0.049 | 0.022 | - | - |
| 53 | 1.000 | 0.000 | 0.000 | 0.000 | 0.20 | 0.10 | - | - |
| 54 | 1.000 | 0.000 | 0.000 | 0.000 | 0.041 | 0.014 | - | - |
| 55 | 1.000 | 0.000 | 0.000 | 0.000 | 0.068 | 0.034 | - | - |
| 56 | 1.000 | 0.000 | 0.000 | 0.000 | 0.076 | 0.022 | - | - |
| 57 | 1.000 | 0.000 | 0.000 | 0.000 | 0.067 | 0.02 | - | - |

### Table B.3. Transformer Tap setting

| From Bus | To Bus | Tap Setting Value (p.u.) |
|---|---|---|
| 4 | 18 | 0.97 |
| 4 | 18 | 10.43 |
| 21 | 20 | 1.043 |
| 24 | 26 | 1.043 |
| 7 | 29 | 0.967 |
| 34 | 32 | 0.975 |
| 11 | 41 | 0.955 |
| 15 | 45 | 0.955 |
| 14 | 46 | 0.9 |
| 10 | 51 | 0.93 |
| 13 | 49 | 0.895 |
| 11 | 43 | 0.958 |
| 40 | 56 | 0.958 |
| 39 | 57 | 0.98 |
| 9 | 55 | 0.94 |
| 24 | 24 | 1.000 |
| 24 | 25 | 1.000 |

### Table B.4. Capacitor Data

| Bus No. | Susceptance (p.u.) |
|---|---|
| 18 | 0.10 |
| 25 | 0.059 |
| 53 | 0.063 |

# BRIEF PROFILE OF AUTHOR

Anubha Gautam was born in 1979 in India. She obtained her Bachelor of Engineering from Rajiv Gandhi Prodyogiki Vishwavidyalaya, Bhopal, India in 2002. She obtained Master of Technology (Heavy electrical Equipment) from Maulana Azad National Institute of Technology, Bhopal in 2007. She has completed Ph.D. in the Electrical Engineering Department from J.C.Bose University of Science and Technology, YMCA Faridabad. She has experience of 18 years of teaching. Her area of interest is Power Electronics and Power systems.

## LIST OF PUBLICATIONS OUT OF THESIS

| S No. | Title of the Paper | Name of the Journal | No. | Volume & Issue | Year | Pages |
|---|---|---|---|---|---|---|
| **1** | Anubha Gautam, P. R. Sharma, and Yogendra Kumar "Mitigating congestion by optimal rescheduling of generators applying hybrid PSO–GWO in deregulated environment" | Springer Nature Applied Sciences (Sc opus Indexed) | 69 | 3/1 | 2021 | |
| **2** | Anubha Gautam, P. R. Sharma, and Yogendra Kumar "Sensitivity Based Congestion Management in a Deregulated Power System by Optimal Allocation & Parameter Setting of TCSC using Grey Wolf Optimization" | International Journal on Electrical Engineering and Informatics (Scopus Indexed) | 12 | 4 | 2020 | 890-911 |
| **3** | Anubha Gautam, P. R. Sharma, and Yogendra Kumar "Mitigating Congestion in Restructured Power System using FACTS Allocation by Sensitivity Factors and Parameter Optimized by GWO" | Advances in Science, Technology and Engineering Systems (Scopus Indexed) | | 5/5 | 2020 | 1-10 |
| **4** | Anubha Gautam, P. R. Sharma, and Yogendra Kumar "ATC Evaluation and Maximization by Optimal Sizing & Location of TCSC using Grey Wolf Optimization" | International Journal of Engineering and Advance Technology (Scopus Indexed) | | 8/5 | 2019 | 1980-1989 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **5** | Anubha Gautam, P. R. Sharma, and Yogendra Kumar "Real & Reactive Power Loss Minimization in Power System by Optimizing Size and Location of TCSC & SVC Using Grey Wolf Optimisation" | Journal of Emerging Technology and Innovative Research (UGC Approved) | | 5/9 | 2018 | 270-285 |
| **6** | Anubha Gautam, P. R. Sharma, and Yogendra Kumar "A review on Congestion management utilizing FACTS devices in deregulated environment with security constraint" | Journal of Emerging Technology and Innovative Research (UGC Approved) | | 5/6 | 2018 | 127-133 |
| **7** | Anubha Gautam, P. R. Sharma, and Yogendra Kumar "Congestion Management by Sensitivity based approach for optimal allocation & parameter setting of TCSC using Grey Wolf optimisation" | IEEE Conference on Power, Control and Computing Technologies (ICPC2T) (Scopus Indexed) | 19535425 | | 2020 | 50-55 |
| **8** | Anubha Gautam, P. R. Sharma, and Yogendra Kumar "Sensitivity based ATC Maximization by Optimal Placement of TCSC applying Grey Wolf Optimization" | International Conference on Recent Developments in Control, Automation and Power Engineering, RDCAPE (Scopus Indexed) | 19322228 | | 2019 | 313-318 |

# LIST OF ACCEPTED PAPERS

| S No. | Title of the Paper | Name of the Journal where accepted | No. | Volume/ Issue | Year |
|---|---|---|---|---|---|
| **1.** | Anubha Gautam, P. R. Sharma, and Yogendra Kumar “A Novel method to reduce congestion in DPS applying TCSC” | Lecture Notes in Electrical Engineering | | | 2022 |

# CONGESTION MANAGEMENT IN DEREGULATED POWER SYSTEM

## SUMMARY

***Submitted in fulfilment of the requirement of the degree of***

**DOCTOR OF PHILOSOPHY**

***to***

***J C BOSE UNIVERSITY OF SCIENCE & TECHNOLOGY, YMCA, FARIDABAD***

***by***

**ANUBHA GAUTAM**

Registration No. YMCAUST/PH14/2011

***Under the Supervision of***

**Dr. P. R. SHARMA** **Dr. YOGENDRA KUMAR**

**PROFESSOR** **PROFESSOR**

**Electrical Engineering Department**

**Faculty of Engineering**

**YMCA University of Science & Technology**

**Sector-6, Mathura Road, Faridabad, Haryana, India**

**April 2022**

# DECLARATION

I hereby declare that this thesis entitled **CONGESTION MANAGEMENT IN DEREGULATED POWER SYSTEM** by **ANUBHA GAUTAM**, being submitted in fulfilment of the requirement for the Degree of Doctor of Philosophy in ELECTRICAL ENGINEERING under Faculty of Engineering of J C Bose University of Science and Technology, YMCA , Faridabad, during the academic year 2021-2022, is a bona fide record of my original work carried out under guidance and supervision of **Dr. P. R. SHARMA, PROFESSOR, ELECTRICAL DEPARTMENT** , J C Bose University of Science and Technology, YMCA, Faridabad and **Dr. YOGENDRA KUMAR, PROFESSOR, ELECTRICAL DEPARTMENT**, MANIT, Bhopal and has not been presented elsewhere.

I further declare that the thesis does not contain any part of any work which has been submitted for the award of any degree either in this university or any other university.

ANUBHA GAUTAM

YMCAUST/PH14/2011

# CERTIFICATE

This is to certify that this Thesis entitled **CONGESTION MANAGEMENT IN DEREGULATED POWER SYSTEM** by **ANUBHA GAUTAM**, submitted in fulfilment of the requirement for the Degree of Doctor of Philosophy in **ELECTRICAL ENGINEERING** under Faculty of Engineering of J C Bose University of Science and Technology, YMCA, Faridabad, during the academic year 2021-2022, is a bona fide record of the work carried out under our guidance and supervision.

We further declare that to best of our knowledge the thesis does not contain any part of any work which has been submitted for the award of any degree either in this university or any other university.

Dr. P R Sharma
Professor
Department of Electrical Engineering
Faculty of Engineering
J C Bose UST
Faridabad

Dr. Yogendra Kumar
Professor
Department of Electrical Engineering
MANIT
Bhopal

Dated:

# TABLE OF CONTENT

# 1. MOTIVATION

The traditional power systems have been known as vertically Integrated systems where the generation, transmission, and distribution are handled by a single entity for a particular geographical location. This system was somewhat easier to coordinate as the whole of the functions have been controlled by a single operator and had only one technical objective of supplying good power quality. Thus, the regulations for electricity were intended only for protecting the consumers from exploitation and to recover the expenditure as capital and operational cost. The need for liberalization or in other words "deregulation" came into existence due to some major concerns aroused due to population growth and the industrial revolution. The main reasons to apply deregulation in the power market can be summarised as below:

## 1.1 Regulation rules become obsolete

The original need for regulation was to give a competition-free environment for the utilities to expand and to recover the initial capital cost invested. The power system framework once developed, only required the operational charges to be recovered in the form of electricity consumption charges from the end-users. These charges have been taken from the customers for so long time that at the starting of 21th Century, the utilities have recovered the finance government has invested. The collection has been reached that amount that after taking the profit out the remaining was reinvested in the expansion of the power system. Also, with time the technology has developed new tools and techniques which made the system approximately risk-free to be invested. Electricity has been treated like a commodity that can be purchased at any time from the market with variable rates in accordance with availability. Thus, the necessity of the "regulations" for governing the power system by the electrical utilities has been absconded.

## 1.2 Accepting private investments

As time passed, with liberalization private investors have been invited to participate in a generation. The reason for such implication been the exponential expansion of loads and deficiency of finance with the government. The power system cannot be expanded to match the pace of development as it requires a lot of finance. Thus, private generators nearby load centres have been invited for investment. The idea for such participation came from the technological development of modern industries governed by the private sector.

## 1.3 Development of advanced technology

With the development of new cutting-edge technology, the way to think about power system development and customer interaction has been changed a lot. This was not possible with the involvement of the government sector only due to the policies made with a different objective and mode of operation to achieve it. Technological developments had made the "regulated power system" obsolete.

### 1.4 Vision towards customer

The traditional "Regulated" power system responded to a customer only when the customer reached the utility, after going through details provided by him. This took a long time to settle down the needs of the customer. Here the customer has not been classified as a promising profit-giving customer or a normal customer. Every customer has been seen as the same. But with technological development, the changing demand of customers has been seen and judged in advance to give him the desired service with higher gains in return. This way of seeing and treating the customer has been started a new trend of deregulation.

Deregulation in power system had brought a number of advantages as compared to the previously regulated system [1]-[3]:

a) Competition in distribution through open access system.
b) Encouraging captive power generation.
c) Unbundling in State Electricity Boards.
d) Promotes competition.
e) Protecting the interests of consumers.
f) Rural Electrification.
g) Rationalization of electricity tariff.
h) Delicensing in a generation.
i) Non-discriminatory open access of the transmission system.

## 2. LITERATURE REVIEW

An extended literature survey has been carried out for understanding congestion and the methods to mitigate it. Table 1 elaborates the findings in literature reviewed. Different technical and non-technical methods are studied extensively for mitigating congestion with the limitations faced in their application. A number of heuristics and metaheuristic methods are prescribed in literature for mitigating congestion. These methods have been given a thorough reviewing to understand the advantages and disadvantages.

**Table 1: Literature Review**

| Author name and Publication Year | Work done in Paper | Limitations of method Applied |
|---|---|---|
| Kaltenbach J C, Peschon J, 1970 [4] | A computational procedure for system planning is presented this procedure Combines and optimizes the formerly separate computations of Load flow, reliability analysis, and economic evaluation. This procedure has been applied successfully to a 17-node system so that the disturbances in heavily loaded line may not affect the rest of the system. | The results obtained by 17 Node system, which has been tested here, cannot be implemented for different standard system, authenticated by technical societies. |
| Carson T, Guy S, Adel H, 1994 [5] | Modelling of SVC is described as standard for Electrical Utility industries. Apart from transient stability program modeling, a long term dynamic programming is described. | The guidelines given for correct use of models in power flow programs are not suitable and practical for expanding power systems with increased load demand. |
| K. R. S. Reddy, N. P. Padhy and R. N. Patel, 2006 [6] | Algorithm for congestion management using OPF is proposed by the application of GA to find optimal scheduling of power flow. Two FACTS devices UPFC and TCSC are optimally located using thermal constraints of line. | Two UPFC and one TCSC gave optimal line loading for previously loaded congested lines. The cost of UPFC is very high and at least two UPFC together with one TCSC is required for a small contingency. For larger and complicated system this cost will be too high and result in high prices for electricity consumers. |
| Acharya, N and Mithulananthan N, 2007 [7] | Series FACTS device, TCSC, is located by LMP difference congestion rent contribution methodologies for mitigating congestion. IEEE 14, 30 and 57 bus system are used as test systems. | The congestion is mitigated by using LMP and congestion rent methods. With the increased complexity of the system, these methods become very tedious and the location of device obtained is not very op[timal. |
| Gitizadeh, M., Kalantar, M., 2008 [8] | TCSC and SVC are used to avoid congestion. GA, fuzzy and sequential quadratic programming are used to get optimal location of FACTS devices. Results validated on IEEE14 bus system. The objective function is to enhance voltage stability margin and security margin of system. | The algorithm is tested only tested on a small non-complex system and is not validated on higher order system. When location of FACTS is to be optimized for higher order system, some alterations are to be done. |
| Hashemzadeh H and Hosseini S H, 2009 [9] | PSO is implemented for locating TCSC to reduce congestion of system by minimizing the objective function which includes congestion cost and total generation cost. Results validated on IEEE 14 and 57 bus system. | Here line outage sensitivity factors using DC power flow method are used to reduce the search space of PSO. This method can be helpful for smaller systems, for large systems it is very difficult to analytically quantify the errors introduced with the dc power flow. |

| | | |
|---|---|---|
| Mandala M, Gupta C P, 2010 [10] | TCSC is used for reducing transmission losses and generation cost while increasing the loadability of line with increased stability of system. Real power performance index (PPI) is the base for optimal location of TCSC to mitigate congestion. Three locations are obtained by PPI and the optimized location is decided by minimizing production cost using interior point methods. | In large and complex systems, the location of FACTS devices by utilizing sensitivity factors produces error in the location prediction. Unless some penalty factor is incorporated. Here no such factors are implemented. |
| Vijayakumar K., 2011 [11] | TCSC and UPFC are placed to relive congestion in IEEE 57 bus system. The location is optimized using GA. | Only the technical benefits of TCSC and UPFC are considered here in terms of loadability of line. The economical criteria is not considered here. Social welfare maximization and line overloading problem are solved separately in this paper. The two may be considered simultaneously by using other optimization methods. |
| Anwar N, Siddiqui A S and Umar A, 2012 [12] | A method where FACTS are clubbed with Power Oscillation Damper (POD) is implemented here for series voltage compensation. UPFC is found more suitable for decongesting the bus as compared to SSSC. | UPFC is quit a costly installation as compared to SSSC. Moreover, it is used with POD which makes the combination not suitable for social welfare. Thus, economic consideration makes this method not appropriate for decongesting the system. |
| Ashwani K, Charan S., 2013 [13] | Third generation of FACTS device, STATCOM, is used in this paper. Its effect on optimal rescheduling of generators is studied for reducing the congestion cost. Three bid block structure is used with static security and voltage margin limits. | The method applied here gives most economical congestion costing only when the rescheduling is done with the incorporation of renewable energy systems. |
| Siddiqui, A.S., Deb, T, 2014 [14] | This paper investigate the effect of SVC, TCSC and UPFC devices on power flows and bus voltages with increased line loadings. IEEE 14 bus system is tested | In this paper all the three devices are used . The series device improved line flow, the shunt device improved voltage profile and the series shunt device UPFC managed both. No special method for location is adopted. |
| Singh J G, Singh S N and Srivastava S C, 2016 [15] | UPFC is implemented in Indian 75 bus system and new England 39 bus system for mitigating congestion. The location of UPFC is determined by power transmission congestion distribution factors (PTCDFUs). | The congestion cost is reduced and the active power rescheduled is quit low. But the shortcoming of this paper is mentioned in paper conclusion that if cost of UPFC is considered this method is not suitable to be applied for. |
| Gupta S K, N. Yadav K and Kumar M, 2018 [16] | In this paper IPFC, UPFC and HVDC are used with generator rescheduling to get the congestion cost in standard IEEE 30 bus system. Here congestion cost with IPFC comes to be less as compared to the other FACTS in corporated. | Generator rescheduling itself is a method of congestion management which include cost of rescheduling. Here this rescheduling is done with FACTS device. IPFC is a very costly device, this makes the system extremely costly. |

| | | |
|---|---|---|
| Farahani V Z and Kazemi A, 2006 [17] | Compared the cost free and non-cost-free methods to mitigate congestion. Generator rescheduling and load curtailment is compared with application of FACTS devices for congestion management. | The two methods are compared and both the methods are found effective. Only TCSC is applied and compared. The comparison with other FACTS devices may discriminate clearly the effective method. |
| Mohd Isa A Niimura T, Yokoyama R, 2008 [18] | Physical transmission congestion is relieved by curtailing a small portion of the non-firm transactions. System operator can select the most effective and desirable congestion relief measures. | Load curtailment is applied together with generator redispatch for mitigating congestion. Generator rescheduling cost is not considered. This makes system uneconomical. |
| Hazra J, Sinha A K , Phulpin Y, 2009 [19] | This paper presents a sensitivity-based congestion management technique based on generation rescheduling and/or load shedding. Sensitivity index relates line current with respect to change in bus injections. | Load curtailment directly increases the congestion cost. Here only generator rescheduling is not mitigating congestion but load curtailment has to be done. This makes the process uneconomical. |
| Md Sarwar, Shahzad A Siddiqui, 2015 [20] | The congestion is alleviated by optimally rescheduling the active power outputs of generators selected based on the magnitude of generator sensitivities to the congested line. The cost of rescheduling is minimized using PSO-ITVAC. The proposed algorithm is tested on IEEE 30-bussystem and IEEE 118-bus system. | The algorithm authenticity may be validated by comparing the results by some other algorithm. |
| Verma S, Mukherjee V, 2016 [21] | The proposed approach of the present work employs firefly algorithm (FFA) for alleviation of transmission network congestion in a pool based electricity market via active power rescheduling of generators, with an objective of reduced congestion cost. | Use of sensitivity factors for selection of participating generators along with rescheduling may be used instead of only applying FFA. |
| Verma S, Saha S, Mukherjee V,<br>2016 [22] | This paper applies Teaching Learning based algorithm with an aim of effectively relieve congestion in the line with minimum deviation in initial generation and, hence, congestion cost. | The algorithm may be applied on more complicated system for validation. |
| Chintam J, Daniel M, 2018 [23] | In this paper, a meta-heuristic satin bowerbird optimization (SBO) algorithm is presented for congestion management (CM) in the deregulated power system. The CM is done in the transmission lines using a generation rescheduling-based approach. | It can be inferred from the single-objective and multi-objective cases that the optimization of one of the objectives has a deteriorating effect on the other objective. Method may be applied as per this. |

## 3. CONGESTION

Deregulation together with advantages has brought certain detriments to the power system. One of the minuses is congestion in the system. Congestion is one of the major technical issues prevalent both in a vertically integrated system and deregulated power system. With the deregulations and participation of private generators, the pre-existing transmission lines are heavily loaded. The lines are continuously working at their thermal and voltage limits. The condition which results in an inability of lines to transmit the demanded power is termed congestion. Congestion in extreme cases can cause severe damage to the system. Congestion in the system has the following ill effects:

a) System disturbances which in extreme cases may lead to system outage due to interconnections.
b) Loss of expensive and important equipment responsible for system security.
c) Power quality degrades while the reliability of transmission reduces.[24], [25]
d) Increased transmission losses reducing the efficiency of the system and have a bad impact on power system economics [24],[25]
e) Ignoring congestion may lead to frequent blackouts resulting in adverse socio-economic consequences [24]-[26].
f) Increased prices that consumer has to pay for limited supplies.
g) All available generators cannot participate in the generation.

## 4. MITIGATING CONGESTION

For mitigating congestion, several techniques have been suggested in the literature. Congestion management can be done by considering the operational cost of the system. Based on the operational cost the technique may be cost-free (with no impact on operational cost) and non-cost-free (include the impact on operational cost). The cost-free methods are also called technical methods which include phase shifting or tap changing of transformers. Phase shifting of transformers has been implemented for a 24-hour schedule instead of current utilization only [27] and utilization of FACTS devices. Out of these two methods, the FACTS application is the most widely used method for managing congestion [28][29]. Other methods of congestion management are non-technical methods that impact operational costs. Generation Rescheduling (GR) [30], Distributed Generation (DG) [31], curtailment of load [32], and nodal pricing-based methods are categorized under non-technical methods.

## 5. OBJECTIVES OF PROPOSED WORK

With the increased power demand and limited power system framework, the transmission lines are overloaded. This overloading results in power loss and system insecurity. There is a deviation in the voltage profile which at its extreme condition may result in blackouts. With higher congestion in the system, the power losses increase manifold. These problems are to be dealt with new technologies and methods so as to make the system economical and secure. An inefficient power system results in higher energy price, which ultimately has to be paid by the consumer. Keeping in view the above-mentioned important issues, the purpose of the work is to develop and implement new technologies and methodologies with the help of an efficient algorithm. Following are the objectives selected for the proposed research work:

### 5.1 To reduce active and reactive power losses by optimal placement of FACTS devices in a power system.

**Solution:** OPF has been performed with Newton Raphson's (NR) load flow analysis. The FACTS devices, SVC and TCSC are located on IEEE 30 Bus system. FACTS are located with the help of Grey Wolf Optimization (GWO) and MATLAB/ SIMULINK. The results clearly indicated that TCSC outperformed SVC when the power loss in the system is concerned. Here since the method applied is a cost-free method i.e. operational cost is kept constant, thus economics concerned with the capital and installation cost of FACTS is not considered.

### 5.2 To enhance Available Transfer Capacity and to minimize the losses using FACTS devices.

**Solution:** ATC being calculated by implementing Power Transfer Distribution Factors (PTDF). The FACTS device used here is TCSC. As TCSC is a series FACT device, it has the capacity to regulate the line reactance directly to manipulate power flow through the line. Location of TCSC is obtained by the PTDF and its reactance is varied using GWO. The changed reactance values are applied to OPF through NR and new line flows are calculated. The location and sizing of TCSC which gives the maximum value of ATC and corresponding minimum values of power loss is the solution of the objective. The SIMULINK is operated two times. First time for ATC enhancement and the second time for power loss reduction. The OPF results for IEEE 30 bus system are compared between GWO and Firefly Algorithm (FA). GWO outperformed FA.

### 5.3 To determine the optimal location and parameter setting of FACTS device for congestion alleviation

**Solution:** This objective is achieved by creating congestion in the system by out-aging the line between two buses and system overloading by 150% and 180%. Then with the utilization of the sensitivity factor’s optimal location of FACTS has been obtained and the parameter setting is done by applying the optimization methods. Here a new methodology to merge two well-known optimization techniques is also proposed. The results validate the methods as the objective is achieved.

### 5.4 To improve voltage stability and enhancement of system security under the congested condition of power system using FACTS devices.

**Solution:** To manage congestion using the FACTS device, it is necessary to optimally locate it. Optimization of the control parameter, like reactance in the case of TCSC, plays a vital role in reducing congestion. The location of TCSC is optimized by a sensitivity factor called Line Utilization Factors (LUF) and Disparity Line Utilization Factors (DLUF). The line with the minimum value of DLUF is the location of TCSC. The reactance setting of TCSC is done with GWO so as to reduce voltage deviation and enhance the security margin of the system. This ultimately reduces congestion in the system to make it stable.

### 5.5 To manage congestion by using Rescheduling of the generators to reduce congestion cost.

**Solution:** This is one of the cost-free methods to mitigate congestion in the power system. Different generators of a system have a tendency to affect the line flows of particular line/s. The individual effect of change in active power output of generator on congested lines is evaluated in contingency condition with the help of Generator Sensitivity Factor (GSF). The generator with a maximum negative GSF value will participate in rescheduling. The extent of rescheduling is decided by GWO and the newly developed Hybrid PSO-GWO (HPSOGWO) so that congestion cost is minimum. PSO, GWO, and HPSOGWO are compared and HPSOGWO is found to be the best of the three.

## 6. METHODOLOGY ADOPTED

Managing congestion is one of the important control activities in a power system. optimal power flow (OPF) has been the most significant technique for obtaining minimum cost generation patterns in a power system with existing transmission and operational constraints. Various optimization techniques can be used to solve OPF problems. These may be a sequential, quadratic, linear, nonlinear, integer, and dynamic programming methods. NR-based methods, interior-point methods, etc. Nonlinear programming methods involve nonlinear objective and constraint equation. A number of heuristic methods are being discussed in the literature. Out of these, GWO is proposed to iterate the non-linear power system equations. Both cost-free and non-cost- free methods have been applied to mitigate congestion in the power system [33]. In the cost-free method, FACT (TCSC) is applied to the system for manipulating the line reactance and hence the power flow. Different sensitivity factors such as LUF, DLUF, ACPTDF have been implemented for FACTS allocation. TCSC parameters are controlled and optimized by GWO. GSF has been used as a sensitivity factor to select a generator for rescheduling. Different evolutionary programming methods such as FA, PSO, and GA are compared with GWO.  A new methodology to merge PSO and GWO has been proposed which includes initialization by PSO which is the strength of PSO and definite convergence which is the strength of GWO. The results show the supremacy of HPSOGWO over other algorithms.

## 6.1 APPLICATION OF FACTS TO REDUCE POWER LOSSES

With technological advancements in power electronics, FACTS devices have been implemented in a huge segment of the power system. These devices elevate the performance characteristics of power system components to increase the efficiency and reliability of the system [34],[35]. The utilization of the installed capacity of the existing power system has been increased manifolds by the implementation of FACTS devices in transmission and distribution networks. Maintaining voltage profile and controlling reactive power are the areas of concern for maintaining stability in EPS. To maintain the quality of power in the system V-Q characteristics must be under control. Reactive power control permits a way to stabilize the voltage profile, effective and efficient utilization of power transfer capabilities, and enhancement of stability range of the system [36], [37]. In this research, TCSC and SVC are implemented to reduce active and reactive power losses.

Real and reactive power losses can be modeled as:

$$T_{ij} = V_i^2 G_{ij} - V_i V_j \{ G_{ij} cos(\theta_i - \theta_j) + B_{ij} sin(\theta_i - \theta_j) \} \tag{1}$$

$$T_{ji} = V_j^2 G_{ij} - V_i V_j \{ G_{ij} cos(\theta_i - \theta_j) - B_{ij} sin(\theta_i - \theta_j) \} \tag{2}$$

here,

$T_{ij}$ : Active power flowing from bus i to bus j

$T_{ji}$ : Active power flowing from bus j to bus i

The net active power loss, $P_L$ can be calculated as:

$$P_L = G_{ij} \left\{ \left( (V_i - V_j \right)^2 + V_i V_j \left( \theta_i - \theta_j \right)^2 \right\} \tag{3}$$

Similarly, the reactive power loss can be calculated as:

$$Q_{ij} = V_i^2 B_{ij} - V_i V_j \left( B_{ij} cos\theta_{ij} + G_{ij} sin\theta_{ij} \right) \tag{4}$$

$$Q_{ji} = V_j^2 B_{ij} - V_i V_j \left( B_{ij} cos\theta_{ij} - G_{ij} sin\theta_{ij} \right) \tag{5}$$

here,

$Q_{ij}$ : reactive power flowing from bus i to bus j

$Q_{ji}$ : reactive power flowing from bus j to bus i

Net reactive power loss, $Q_L$ can be calculated as:

$$Q_L = B_{ij} \left( \left( V_i - V_j \right)^2 + V_i V_j \theta_{ij}^2 \right) \tag{6}$$

The power losses are calculated with the help of OPF with Newton Raphson load flow analysis without applying TCSC and SVC.

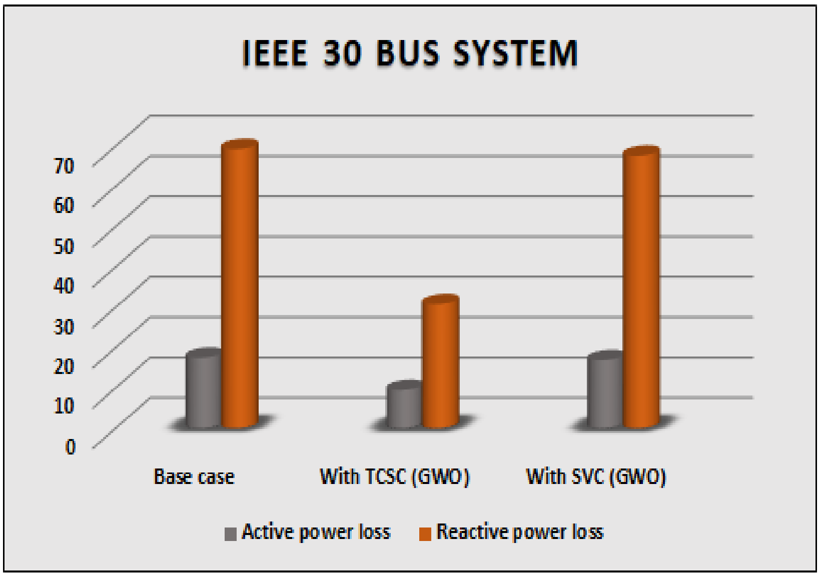

**Figure1. Active and Reactive power loss in IEEE 30 bus system**

Now TCSC and SVC are located and optimized for their respective parameters with the help of the Grey Wolf Optimization (GWO) algorithm and then again OPF with NR load flow is applied to calculate the power losses.

The results obtained are graphically demonstrated in Figure.1 and Figure.2.

Figure.1 and Figure.2 depict that TCSC optimized with GWO for its location and parameters gives significantly improved results as compared to GWO optimized SVC.

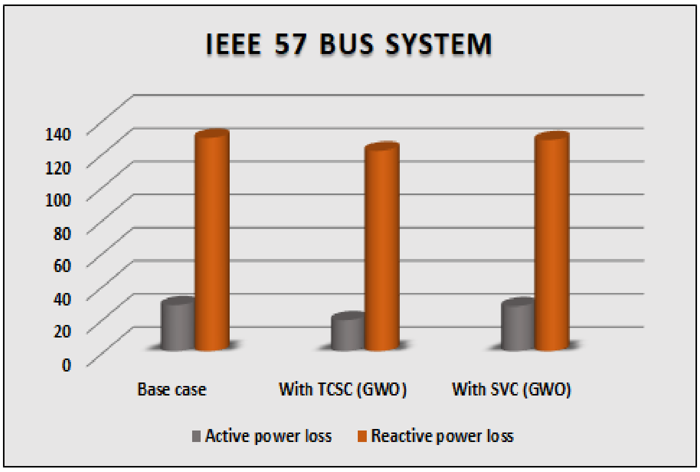

**Figure 2. Active and Reactive power loss in IEEE 57 bus system**

## 6.2 ENHANCEMENT OF ATC TO MITIGATE CONGESTION

A multi-objective function including ATC enhancement and total power loss reduction is being achieved here by implementing the series FACTS device, TCSC. The location of TCSC is decided with the help of ACPTDF as the sensitivity factor while the TCSC parameter is optimized with the help of the GWO algorithm. These two conflicting objectives are effectively treated and while enhancing ATC the power losses are also increased but are reduced by about 15% as compared to that enhanced without TCSC implementation.

Moreover, the reduction in ATC value while reducing power losses is 10% less as compared to that reduced without TCSC. Here, the location of TCSC with ACPTDF and optimization of parameter setting with GWO has increased the ATC value effectively with a reduction in increment of power losses with it.

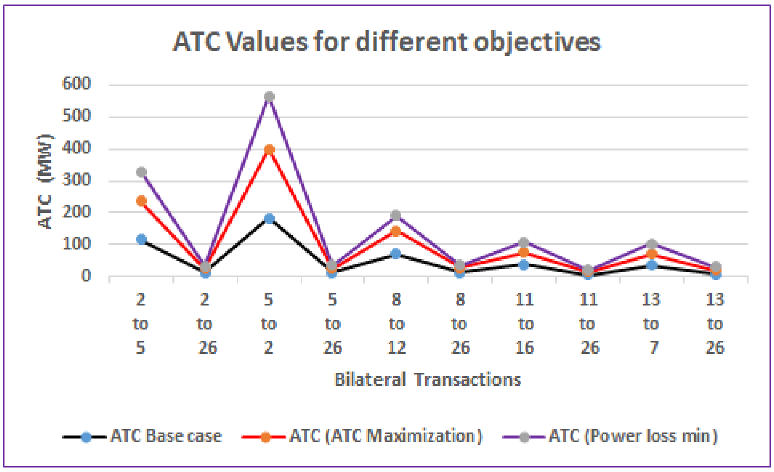

**Figure 3: ATC values obtained for different objectives**

In an interconnected power system, the ATC value for the line connected between far away situated buses is less as compared to the ATC for nearby situated buses.

In this part of the research, the ATC value is enhanced for the line between far away buses as compared to that for the system without TCSC, which is the significant result obtained out of the multi-objective function.

Figure.3 presents the results obtained for the objective function considered. TCSC location has been optimized successfully with suitable parameter setting well within defined limits (0.2pu to -0.8pu). As the ATC value is enhanced together with the reduction in power system losses the objective of mitigating congestion is achieved.

### 6.3 SECURITY ENHANCEMENT WITH VOLTAGE PROFILE IMPROVEMENT TO MITIGATE CONGESTION USING HPSOGWO

Multi-objective function including power loss reduction, voltage deviation reduction, improvement of security margin and redistribution of power flows through the transmission lines is being achieved for mitigating congestion with the implementation of TCSC has been illustrated. TCSC being located with the help of the Disparity line utilization factor (DLUF). Line Utilization Factor (LUF) of different lines is calculated and then the results are sorted for the most congested line. This loading on this congested line has to be reduced by optimally placing TCSC. For getting the optimal location, DLUF for the lines connected to the most congested line is calculated. The line with a minimum value of DLUF is the best location of TCSC. Constrained OPF with NR is carried out to solve the objective function. A comparative analysis of the results obtained with the implementation of GWO, PSO, and HPSOGWO has been done. Single line outage, 150% system overloading, and 180% system overloading are considered as contingency conditions here. At normal operating conditions the overall power loss is reduced by 34%, 42%, and 48% respectively when TCSC optimized with PSO, GWO, and HPSOGWO is incorporated in the system.

The redistribution of Line Utilization Factor (LUF) has been achieved which in turn resulted in the redistribution of power flows in the lines. Power flow through Congested lines has been reduced while the underloaded lines are loaded suitably. Similarly, other parameters i.e., reduction in voltage deviation and the security margin of the system have been optimized and significantly better results with HPSOGWO in comparison to the parent algorithms are obtained.

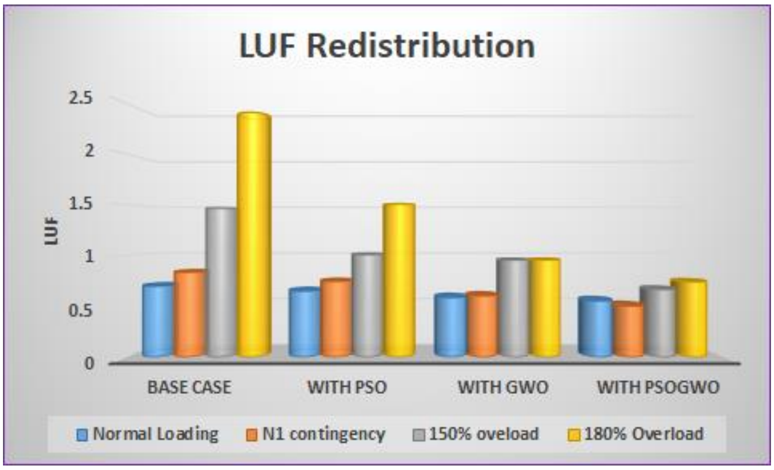

**Figure 4: LUF redistribution for redistributed power flows**

Congestion is thus mitigated with reduced power loss and voltage deviation. The security margin has been improved considerably.

Figure. 4 shows the LUF redistribution for different contingency conditions. The maximum values of LUF are reduced considerably with the application of HPSOGWO.

### 6.4 CONGESTION MITIGATION BY GENERATOR RESCHEDULING

A novel method to merge two well-known algorithms is presented in this chapter. The effectiveness

A novel method to merge two well-known algorithms is presented in this chapter. The effectiveness of the new algorithm is validated on the standard IEEE 30 bus system. The generator participating in the process of rescheduling being very efficiently selected with the help of the Generator Sensitivity Factor (GSF) while the magnitude of active power for which the selected generator is rescheduled is carried out with the help of the Hybrid PSO-GWO algorithm. Here also two contradicting objectives i.e. real power rescheduling of generators and congestion cost or cost of rescheduling are considered together. The objective function of minimizing the cost of congestion is effectively achieved here with the least deviation of active power rescheduling of generators. The method includes the calculation of GSF for all the generators. The generators with most negative and non-uniform values of GSF are the one which will participate in rescheduling process. Thus, the generator participating in rescheduling is searched here with GSF and the value of active power for which the participating generator is rescheduled is optimized with the proposed algorithms. The respective optimized parameters are compared for GWO, PSO, and HPSOGWO where the hybrid algorithm developed evaluated the objective function most effectively and in a minimum number of iterations.

## 7. OUTCOMES OF RESEARCH

The transmission test system studied with the line limits, standard voltage values of buses, total active power loss is minimized concurrently fulfilling all the equality and inequality constraints under consideration. The thorough evaluation and assessments carried out with the objective of deciding the best methodology for the problem specified in the thesis applied to the transmission systems considered, the below-mentioned interpretations and conclusions have been drawn:

1. The congestion mitigation by using LMP and congestion rent methods is effective on small systems, with the increased complexity of the system, these methods become very tedious and the location of TCSC and SVC obtained is not very optimal.
2. The Evolutionary algorithms (PSO, GWO, and FA) require less computation time and give improved results in terms of reduced power transmission limit, suitable voltage profile, reduced active power loss in the system considered.
3. For the test systems under consideration in this research, comparing all the algorithms (PSO, GWO, and FA), a small difference is realized when the number of iterations, computational times, and precision of all the results are compared. But with a closer look, it is discovered that PSO gives better results than FA. While GWO outperforms both PSO and FA when the number of iterations and precision of solution of the formulated objective function is considered.

4. When the proposed method for merging PSO and GWO is adopted to design hybrid PSOGWO (HPSOGWO), the convergence characteristics become more suitable for the congested system. Results clearly marked that HPSOGWO has quick convergence and is more precise when congestion cost, rescheduled active power, and minimization of active power loss with a suitable voltage profile is considered.

# REFERENCES

[1] “Power sector reform in India” http://shodhganga.inflibnet.ac.in/bitstream /10603/111787/7/ chapter- 4.pdf.

[2] Anoop Singh, *Power sector reform in India: Current issues and prospects*, Energy Policy, vol. 34, pp. 2480-2490, Sep. 2004.

[3] Anoop Singh, *Towards a competitive market for Electricity and consumer choice in the Indian power sector*, Energy Policy, vol. 38, pp. 4196-4208, May 2010.

[4] J. Kaltenbach, J. Peschon and E. H. Gehrig, “A Mathematical Optimization Technique for the Expansion of Electric Power Transmission Systems”, in *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-89, no. 1, pp. 113-119, Jan. 1970, doi: 10.1109/TPAS.1970.292677.

[5] Carson T, Guy S, Adel H , "Static VAr compensator models for power flow and dynamic performance simulation," in *IEEE Transactions on Power Systems*, vol. 9, no. 1, pp. 229-240, Feb. 1994, doi: 10.1109/59.317606.

[6] K. R. S. Reddy, N. P. Padhy and R. N. Patel, "Congestion management in deregulated power system using FACTS devices," in *IEEE Power India Conference*, New Delhi, 2006, pp. 8 pp.-, doi: 10.1109/POWERI.2006.1632541.

[7] Acharya, Naresh and N. Mithulananthan. “Locating series FACTS devices for congestion management in deregulated electricity markets.” in *Electric Power Systems Research* 77 (2007): 352-360.

[8] Gitizadeh, M., Kalantar, M., “Genetic algorithm-based fuzzy multi-objective approach to congestion management using FACTS devices”, in *Electr Eng* 90, 539–549 (2009). https://doi.org/10.1007/s00202-008-0105-7.

[9] H. Hashemzadeh and S. H. Hosseini, "Locating series FACTS devices using line outage sensitivity factors and particle swarm optimization for congestion management," in *IEEE Power & Energy Society General Meeting*, Calgary, AB, 2009, pp. 1-6, doi: 10.1109/PES.2009.5275773.

[10] M. Mandala and C. P. Gupta, "Congestion management by optimal placement of FACTS device," in *Joint International Conference on Power Electronics, Drives and Energy Systems & 2010 Power India*, New Delhi, 2010, pp. 1-7, doi: 10.1109/PEDES.2010.5712387.

[11] K.Vijayakumar., “ Optimal Location of FACTS Devices for Congestion Management in Deregulated Power Systems”, in *International Journal of Computer Applications* (0975 – 8887) Volume 16– No.6, February 2011.

[12] N. Anwer, A. S. Siddiqui and A. Umar, "Analysis of UPFC, SSSC with and without POD in congestion management of transmission system," in *IEEE 5th India International Conference on Power Electronics (IICPE),* Delhi, 2012, pp. 1-6, doi: 10.1109/IICPE.2012.6450489.

[13] Ashwani Kumar, Charan Sekhar, "Congestion management with FACTS devices in deregulated electricity markets ensuring loadability limit", in *International Journal of Electrical Power & Energy Systems,* Volume 46, 2013, Pages 258-273, ISSN 0142-0615, https://doi.org/10.1016/j.ijepes.2012.10.010.

[14] Siddiqui, A.S., Deb, T., "Congestion management using FACTS devices" in *Int J Syst Assur Eng Manag* 5, 618–627 (2014). https://doi.org/10.1007/s13198-013-0212-3.

[15] J. G. Singh, S. N. Singh and S. C. Srivastava, "Congestion management by using FACTS controller in power system," in IEEE *Region 10 Humanitarian Technology Conference (R10-HTC),* Agra, 2016, pp. 1-7, doi: 10.1109/R10-HTC.2016.7906793.

[16] S. k. Gupta, N. K. Yadav and M. Kumar, "Effect of FACTS Devices on Congestion Management using Active & Reactive Power Rescheduling," in 2nd *IEEE International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES),* Delhi, India, 2018, pp. 50-55, doi: 10.1109/ICPEICES.2018.8897487.

[17] V. Z. Farahani and A. Kazemi, "Comparing two ways of congestion management in bilateral based power market," in *IEEE GCC Conference (GCC), Manama*, 2006, pp. 1-8, doi: 10.1109/IEEEGCC.2006.5686233.

[18] Aishah Mohd Isa Takahide Niimura,, Ryuichi Yokoyama, "Multicriteria transmission congestion management by load curtailment and generation redispatch in a deregulated power system", in *Transactions On Electrical And Electronic Engineering, IEEJ Trans* 2008; 3: 524–529, DOI:10.1002/tee.20308

[19] J. Hazra, A. K. Sinha and Y. Phulpin, "Congestion management using generation rescheduling and/or load shedding of sensitive buses," in *International Conference on Power Systems,* Kharagpur, 2009, pp. 1-5, doi: 10.1109/ICPWS.2009.5442680.

[20] Md Sarwar, Anwar Shahzad Siddiqui, "An efficient particle swarm optimizer for congestion management in deregulated electricity market ", in *Journal of Electrical Systems and Information Technology,* Volume 2, Issue 3, 2015, Pages 269-282, ISSN 2314-7172, https://doi.org/10.1016/j.jesit.2015.08.002.

[21] Sumit Verma, V. Mukherjee, "Firefly algorithm for congestion management in deregulated environment", in *Engineering Science and Technology, an International Journal,* Volume 19, Issue 3, 2016, Pages 1254-1265, ISSN 2215-0986, https://doi.org/10.1016/j.jestch.2016.02.001.

[22] Sumit Verma, Subhodip Saha, V. Mukherjee, “Optimal rescheduling of real power generation for congestion management using teaching-learning-based optimization algorithm”, in *Journal of Electrical Systems and Information Technology,* Volume 5, Issue 3, 2018, Pages 889-907, ISSN 2314-7172, https://doi.org/10.1016/j.jesit.2016.12.008.

[23] Jagadeeswar Reddy Chintam, Mary Daniel, “Real-Power Rescheduling of Generators for Congestion Management Using a Novel Satin Bowerbird Optimization Algorithm”, in *Energies,* 11(1), 183. doi:10.3390/en11010183.

[24] A. Papalexopoulos, “Congestion management in a competitive environment”, in *PICA 1997 Conference, Tutorial on Future Needs and Trends in Power System Computing,* Columbus, OH, May 1997.

[25] W.W. Hogan, “Nodes and zones in electricity markets: seeking simplified congestion pricing”, in *18th Annual North American Conference of the USAEE/IAEE, San Francisco*, California, September 1997.

[26] F.D. Galiana, M. Ilic, “A Mathematical framework for the analysis and management of power transactions under open access”, in *IEEE Trans. Power Syst*. 13 (May (2)) (1998) 681–687.

[27] P. Guha Thakurta, D. Van Hertel, and R. Belmans, "An approach for managing switchings of controllable devices in the Benelux to integrate more renewable sources," in *IEEE Trondheim PowerTech*, Trondheim, 2011, pp. 1-7, DOI: 10.1109/PTC.2011.6019240.

[28] L.Rajalakshmi, M.V.Suganyadevi, S.Parameswari, “Congestion Management in Deregulated Power System by Locating Series FACTS Devices”, in *International Journal of Computer Applications* (0975 – 8887) Volume 13– No.8, January 2011.

[29] C Shekhar, A Kumar, “Congestion Management in Hybrid Electricity Markets with FACTS Devices with Loadability Limits”, in *International Journal of Electrical and Computer Engineering,* Vol.2, No. 1, February 2012, pp.75-89.

[30] S. Deb and A. K. Goswami, "Congestion management by generator rescheduling using Artificial Bee Colony optimization Technique," in *Annual IEEE India Conference (INDICON),* Kochi, 2012, pp. 909-914, DOI: 10.1109/INDCON.2012.6420746.

[31] M. Khanabadi, M. Doostizadeh, A. Esmaeilian, and M. Mohseninezhad, "Transmission congestion management through optimal distributed generation's sizing and placement," in *10th International Conference on Environment and Electrical Engineering,* Rome, 2011, pp. 1-4, DOI: 10.1109/EEEIC.2011.5874788.

[32] S. Charles Raja, P. Venkatesh and B. V. Manikandan, "Transmission Congestion Management in restructured power systems," in *International Conference on Emerging Trends in Electrical and Computer Technology,* Nagercoil, 2011, pp. 23-28, DOI: 10.1109/ICETECT.2011.5760085.

[33] V. Z. Farahani and A. Kazemi, "Comparing two ways of congestion management in bilateral based power market," in *IEEE GCC Conference (GCC)*, Manama, 2006, pp. 1-8, doi: 10.1109/IEEEGCC.2006.5686233.

[34] L.Rajalakshmi, M.V.Suganyadevi, S.Parameswari, “Congestion Management in Deregulated Power System by Locating Series FACTS Devices”, in *International Journal of Computer Applications* (0975 – 8887) Volume 13– No.8, January 2011.

[35] C Shekhar, A Kumar, “Congestion Management in Hybrid Electricity Markets with FACTS Devices with Loadability Limits”, in *International journal of Electrical and Computer Engineering*, Vol.2, No. 1, February 2012, pp.75-89.

[36] S. Deb and A. K. Goswami, "Congestion management by generator rescheduling using Artificial Bee Colony optimization Technique," in *Annual IEEE India Conference (INDICON), Kochi,* 2012, pp. 909-914, doi: 10.1109/INDCON.2012.6420746.

[37] M. Khanabadi, M. Doostizadeh, A. Esmaeilian and M. Mohseninezhad, "Transmission congestion management through optimal distributed generation's sizing and placement," in *10th International Conference on Environment and Electrical Engineering,* Rome, 2011, pp. 1-4, doi: 10.1109/EEEIC.2011.5874788.