OPTIMAL PLACEMENT OF MULTIPLE TCSC FOR IMPROVING POWER TRANSFER CAPABILITY

A Project Report

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CERTIFICATE

This is to certify that the report titled **OPTIMAL PLACEMENT OF MULTIPLE TCSC FOR IMPROVING POWER TRANSFER CAPABILITY**, submitted by **Banoth Ganesh Kumar, EE08B007** to the Indian Institute of Technology Madras, for the award of the degrees of **Bachelor of Technology** and **Master of Technology**, is a bona fide record of the project work done by him under my supervision. The contents of this report, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

KEYWORDS: Flexible AC Transmission System, Particle Swarm Optimization, Thyristor Controlled Series Compensator, Total Transfer Capability.

Now-a-days there is a continuous increase in the power demand and power supply. There is a need to increase the power transfer capability of the existing transmission system without violating the system constraints. The Flexible AC transmission system (FACTS) controllers can enable a line to carry power closer to its thermal rating and offers continuous control of power flow or voltage changes, against daily load changes by controlling the parameters that govern the operation of transmission systems like series impedance, shunt impedance, line current, bus voltage, load bus phase angle, and the damping of oscillations at various frequencies below the rated frequency.

TCSC, a series FACTS controller, is used to improve the power transfer capability of the system under steady state conditions. While using TCSC the investment cost should also be taken into consideration. In this thesis, an objective function to find optimal number, location and rating of TCSC to be placed in a system for improving TTC, along with constraints has been developed. This objective function has been solved by Particle Swarm Optimization (PSO). The proposed methodology has been applied to IEEE 6-BUS test system and IEEE 30-BUS test system. The simulation results are presented.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

FACTS	Flexible Alternating Current Transmission System
SVC	Static VAr Compensator
STATCOM	Static Synchronous Series Compensator
SSSC	Static Synchronous Series Compensator
TCSC	Thyristor Controlled Series Compensator
TSSC	Thyristor Switched Series Capacitor
TCSR	Thyristor Controlled Series Reactor
UPFC	Unified Power Flow Controller
TCPST	Thyristor Controlled Phase Shifting Transformer
TCPAR	Thyristor Controlled Phase Angle Regulator
TCVR	Thyristor Controlled Voltage Regulator
TTC	Total Transfer Capability
ATC	Available Transfer Capability
GA	Genetic Algorithm
BA	Bees Annealing
PSO	Particle Swarm Optimization
OPF	Optimal Power Flow
CPF	Continuous Power Flow
RPF	Repeated Power Flow
TCR	Thyristor Controlled Reactor
NERC	North American Electric Reliability Corporation
CBM	Capacity Benefit Margin
TRM	Transmission Reliability Margin
IEEE	Institute of Electrical and Electronics Engineers
IET	Institution of Engineering and Technology

NOTATIONS

$V_i; V_j$	Voltage magnitudes at the buses i and j
$\delta_i; \delta_j$	Voltage phase angles at the buses i and j
I	Magnitude of transmission line current
I'	Magnitude of current in transmission line after including compensator
R	Resistance of transmission line
X	Reactance of transmission line
X_C	Capacitive reactance
X_L	Inductive reactance
$I_d; I_q$	In-phase and quadrature components of the transmission line current
V_{COMP}	Voltage across the compensator
I_{COMP}	Current passing through the compensator
V_{sm}	Voltage across the sending end and midpoint of transmission line
V_{mr}	Voltage across the midpoint and receiving end of transmission line
I_{sm}	Current passing from sending end to midpoint of transmission line
I_{mr}	Current passing from midpoint to receiving end of transmission line
P_{Loss}	Real power loss in transmission system
$P_i; P_j$	Active power injections at buses i and j
$Q_i; Q_j$	Reactive power injections at buses i and j
α_{ij} ; β_{ij}	Loss coefficients
r_n	Resistance of the transmission line n
x_n	Reactance of the transmission line n
B_n	Susceptance of the transmission line n
G_n	Conductance of the transmission line n
x_{TCSC}	Reactance offered by TCSC
X_{Line}	Reactance offered by transmission line
P_{ij}	Active power transferred from bus i to j
Z_{ij}	Impedance of the transmission line connected between buses i and j
R_{ij}	Resistance of the transmission line connected between buses i and j

X_{ij}	Reactance of the transmission line connected between buses i and j
P_{max}	Peak value of the real power power transferred
Q_C	Reactive power injected by the shunt compensator
P_{Gi}	Real power generation at the i^{th} bus
Q_{Gi}	Reactive power generation at the i^{th} bus
P_{Di}	Real power demand at the i^{th} bus
Q_{Di}	Reactive power demand at the i^{th} bus
N	Total number of buses
$N_\circ$	Total number of buses excluding slack bus
V_L	Magnitude of the load voltage
$v(t)$	Sinusoidal input source voltage
ω	Angular frequency
$i_L(t)$	Current through the TCR circuit
$i_{LF}(\alpha)$	Fundamental current through the TCR
α	Triggering angle to the thyristor
σ	Conduction angle of the thyristor
$B_{TCR}(\alpha)$	Susceptance of the TCR
$X_{TCR}(\alpha)$	Reactance of the TCR
$X_{TCSC}(\alpha)$	Reactance of TCSC
C_{TCSC}	Cost function of TCSC
s	Rating of the TCSC in $MVAr$
p_{best}	Particle best value
g_{best}	Particle global best value
x_i	Position of the i^{th} particle
v_i	Velocity of the i^{th} particle
c_1, c_2	Acceleration co-effecients
w	Inertia weight
x_i^k	Position of the i^{th} particle at k^{th} iteration
v_i^k	Velocity of the i^{th} particle at k^{th} iteration

CHAPTER 1

INTRODUCTION

The electrical energy needs are growing continuously around the world and hence there is a continuous increase in the power demand and power supply. This increase in the power has to be transmitted through the transmission lines and if transmission lines reaches its permissible power transfer limits then we need to build new transmission lines in parallel to meet the demand. But, installing new transmission line is more expensive and difficulties encountered in building new transmission lines would often limit the available transmission capacity. So we need some other way of transmitting more power through the transmission line economically.

Loads in a typical power system vary continuously over a day in general and so the power flow in transmission line can vary even under normal, steady state conditions. The occurrence of a contingency (due to tripping of a line, generator, load etc.) can result in overloading of some lines and consequently voltage collapse at buses due to shortage of reactive power. These factors leads to the complexity of maintaining economic and secure operation of large interconnected power system network. The Flexible AC Transmission System (FACTS) technology is essential to alleviate some of these difficulties by enabling utilities to get most services from their transmission facilities and enhance grid reliability [1].A power electronic-based system and other static equipment that provide control of one or more AC transmission system parameters are called as FACTS controllers. By providing added flexibility, FACTS Controllers [1] can enable a line to carry power closer to its thermal rating. These power electronic devices control the power flow and regulate the voltage, against the changing load. These opportunities arise through the ability of FACTS Controllers to control the interrelated parameters that govern the operation of transmission systems including series impedance, shunt impedance, current, voltage phase angle and the damping of oscillations at various frequencies below the rated frequency.

1.1 Classification of FACTS

FACTS devices are broadly classified into four categories depending on the placement of the devices with respect to transmission line and they are given as following [1].

- Series Controllers
- Shunt Controllers
- Combined series-series Controllers
- Combined series-shunt Controllers

Series Controllers: These types of controllers are connected in series with the transmission line. The series controller could be of variable impedance type, such as capacitor, reactor or a power electronic based variable source of main frequency. The basic principle of all series FACTS controllers is that they inject voltage in series with the line. The main series FACTS controllers are given below.

- Static Synchronous Series Compensator (SSSC)
- Interline Power Flow Controller (IPFC)
- Thyristor Controlled Series Capacitor (TCSC)
- Thyristor Switched Series Capacitor (TSSC)
- Thyristor Controlled Series Reactor (TCSR)

Shunt Controllers: These types of controllers are connected in shunt with the transmission line. As in series controller, the shunt controllers may be of variable impedance type, such as capacitor, reactor, variable source or a combination of these. Shunt Controllers inject current into the system at the point of connection. [2] As long as the injected current is in quadrature with the line voltage, the shunt controller only supplies or consumes variable reactive power. Any other phase relationship will involve handling of real power. The main shunt FACTS controllers are given below.

- Static Synchronous Compensator (STATCOM)
- Static Var Compensator (SVC)
- Thyristor Controlled Reactor (TCR)

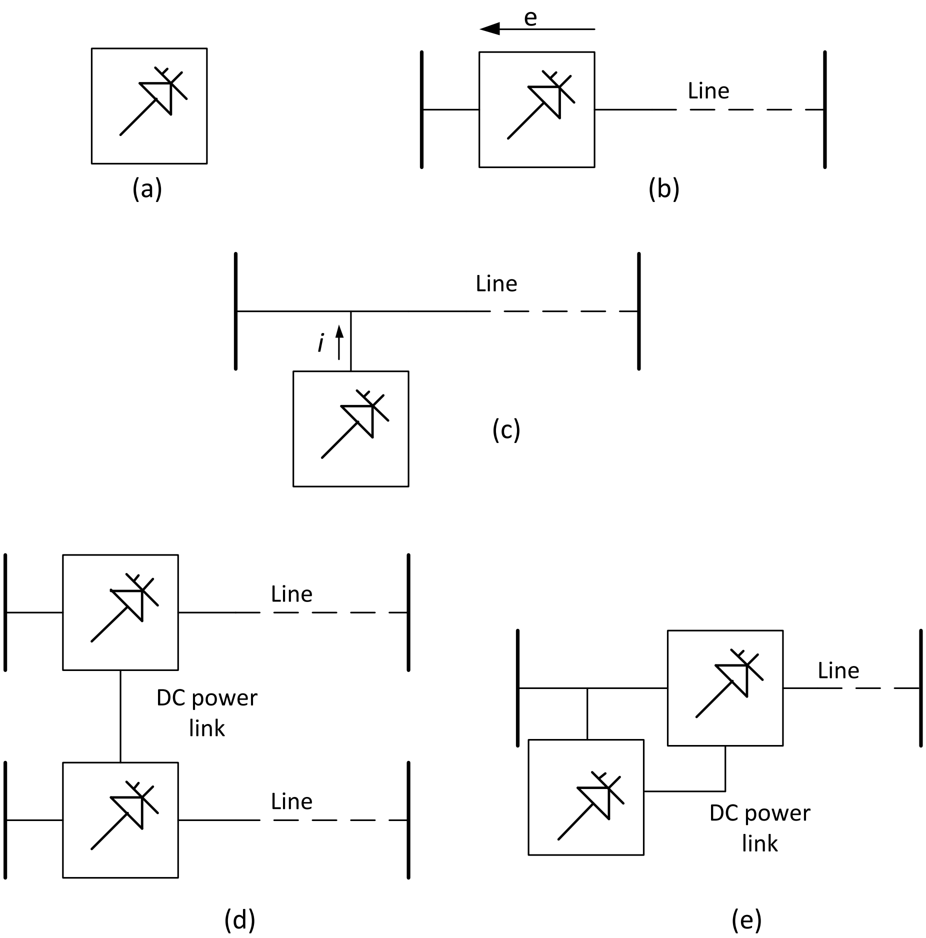

Fig. 1.1 Basic types of FACTS Controllers: (a) general symbol for FACTS Controller; (b) series Controller; (c) shunt Controller; (d) series-series Controller; (e) series-shunt Controller

Combined series-series Controllers: These controllers could be a combination of separate series controllers, which are controlled in a coordinated manner, in a multi line transmission system. Series controllers provide independent series reactive compensation for each line and also transfer real power among lines via DC power link. This real power transfer capability makes it possible to balance both the real and reactive power flow in lines and there by maximize the utilization of transmission system. The Interline Power Flow Controller (IPFC) is the important type of combined series-series controller.

Combined series-shunt Controllers: These controllers could be a combination of separate shunt and series controllers, which are controlled in a coordinated manner, in a multi line transmission system. Shunt part of the controller inject current into the system and Series part of the controller will provide voltage in series in the line. There is real power exchange between the series and shunt controllers via power link. The main series-shunt FACTS controllers are given below.

- Unified power flow controller (UPFC)
- Thyristor controlled phase shifting transformer (TCPST)

The main purpose of the series and shunt FACTS devices is to increase the transmittable power through the transmission line, improve the steady-state transmission characteristics and enhance the stability of the system. In the present work, TCSC is considered to maximize the Total Transfer Capability (TTC).

1.2 Application of FACTS Controllers

There are lot of applications of the FACTS devices in the transmission network during its steady state operating conditions [1] [3]. FACTS technology opens up new opportunities for controlling power and enhancing the usable capacity of present, as well as new and upgraded lines. FACTS-devices provide a better adaptation to varying operational conditions and improve the usage of existing installations. The basic applications of FACTS-devices include power flow control, increase of transmission capability, voltage control, reactive power compensation, stability improvement, power quality improvement, interconnection of renewable and distributed generation and storage. Some of these are briefly explained below.

- **Power flow control:** Without any control, power flow is based on the inverse of various transmission line impedance. One way of controlling the power flow in a line is by changing the impedance of that line. Using power electronic converters, power flow can be electronically controlled. By controlling impedance or phase angle, a series type FACTS controller can control the power flow as required.
- **Power transfer capability:** By controlling the power flow we can increase the power transfer capability using series-shunt FACTS controllers. FACTS concept makes it possible to vary the circuit reactance, voltage magnitude, and phase angle and redistribute line flow and regulate nodal voltage, thereby mitigating the critical situation and increase TTC.
- **Voltage control and reactive power compensation :** Under steady-state conditions, high loading and low voltage are the limiting factors in a regular power system network. Reactive power has to be supplied locally to compensate for the reactive power loss in transmission network. This not only helps in improving voltage but also for power factor correction at the load bus.

- **Stability improvement:** Due to increase in demand some transmission lines are heavily loaded and the system stability becomes a power transfer-limiting factor. Among the various stability limits, voltage and angle stability play an important role in the power system. FACTS devices allow the flexible and dynamic control of power systems by changing three main variables voltage, angle and impedance.
- **Power quality improvement:** When there is a sudden change in load or sudden fault occue in the system, the quality of power gets effected. Power quality is necessary for normal operation of loads as they are designed to operate in specific conditions. FACTS controllers such as STATCOM and DSTATCOM, are used to mitigate the power quality problems such as low power factor, shortage of reactive power, voltage and current harmonics

1.3 Literature review

In recent years, the impact of FACTS devices on power transfer capability enhancement and system loss minimization have been a major concern in the electric power system. The Total Transfer Capability (TTC) is defined as the amount of electric power that can be transferred over the interconnected transmission network in a reliable manner without violating the predefined set of conditions of the system [4]. The various constraints that limit Total Transfer Capability may be the physical and electrical characteristics of the systems including thermal, voltage, and stability limits.

$$TTC = \text{Minimum of } \{\text{Thermal Limit, Voltage Limit, Stability Limit}\}$$

TCSC is one of the most effective measures for enhancing the stability, enhancing the dynamic characteristics of power system, and increasing the transfer capability of the transmission system by reducing the transfer reactance between the buses at which the line is connected. However, to achieve the above mentioned benefits, the TCSC should be properly installed in the network with appropriate parameters. A Newton Raphson load flow algorithm to solve power flow problems in power system with thyristor controlled series capacitor (TCSC) was proposed in [5]. There are several methods available in the literature to optimally place TCSC. Several stochastic search optimization techniques, such as Genetic Algorithm(GA) [6], Particle Swarm Optimization(PSO) [7] were proposed for solving the optimal location of FACTS. However, multiple TCSC placement for improving TTC with minimum cost is not addressed.

1.4 Motivation and Objective

Here we deal with the application of Particle Swarm Optimization (PSO) to find out the optimal number, the optimal locations, and the optimal parameter settings of multiple TCSC devices to maximize the loadability (TTC) of the system with minimum cost of installation of these devices without any violations in the thermal or voltage limits.The main objectives of the present work are

- Optimal placement of multiple TCSC
- Optimal parameter setting of TCSC for improving the TTC with minimum investment cost

Particle Swarm Optimization (PSO) [7] algorithm is used to find the optimal parameter for TCSC to maximize the TTC, with minimal investment cost of the devices without violating the operating constraints. The main advantage of PSO optimization technique is that, it is very simple in terms of mathematical formulation and understating.Unlike Genetic Algorithm(GA), PSO overcomes the premature convergence problem and enhances the search capability.

1.5 Organization of Thesis

Chapter 1 gives a general introduction to the FACTS controllers used in the power system network and their classification. Some application of FACTS Controllers are also discussed. Different optimization methods available in the literature for optimal placement of TCSC and maximizing the TTC are given in brief. Motivation for the research problem, main objectives of the work and organization of thesis are also presented.
Chapter 2 gives a brief introduction about the transmission system with and without series compensation. Power transfer capability enhancement with ideal series compensating devices are explained. The steady state modeling and principle of operation of TCSC devices are explained in detail.
Chapter 3 Determination of TTC with Repeated Power Flow method is explained in detail. Particle swarm optimization method is explained to solve multi objective optimization problem consisting of maximization of TTC, simultaneously with minimum device investment cost without violating system constraints.

Chapter 4 gives the detailed simulation results for the optimal placement of TCSC, and the optimal ratings of TCSC used to maximize the TTC, simultaneously with minimum investment cost. Two different test systems, IEEE 6-BUS system and IEEE 30-BUS system are considered. The simulation results are presented.

Chapter 5 gives the important conclusions and the scope for future work.

The IEEE 6-BUS and the IEEE 30-BUS system system data are given in Appendix A and B, respectively.

CHAPTER 2

PRINCIPLE OF OPERATION AND MODELING OF TCSC

TCSC is an important FACTS controller used for improving the power transfer capability. The principle of operation, modeling aspects and characteristics of TCSC are explained in detail in this chapter.

2.1 Transmission System without Compensation

Figure 2.1 shows the single line diagram of a typical two bus, one generator and one load bus, AC system. In Fig 2.1 $V_1\angle\delta$ is the complex source voltage, $V_2\angle 0$ is the load

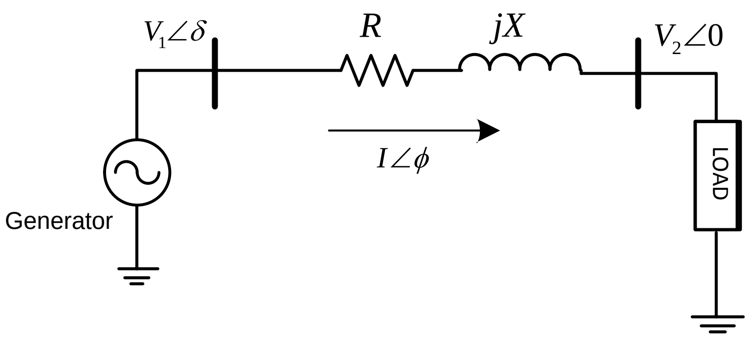

Fig. 2.1 Schematic diagram of AC Power System

voltage, $R + jX$ is the impedance of the transmission line and $I\angle\phi$ is the current in the transmission line. The phasor diagram corresponding to the system shown in Fig. 2.1 is given in Fig. 2.2. The current I can be split into two components: one in-phase (I_d) with the load voltage V_2 and other in-quadrature (I_q) to the load voltage. The reactive power drawn by the load is given as $V_2 I_q$ and this has to be supplied by the source apart from the reactive power drop XI^2. It can be observed from the phasor diagram that as the reactive power requirement increases the current drawn by the load will increase

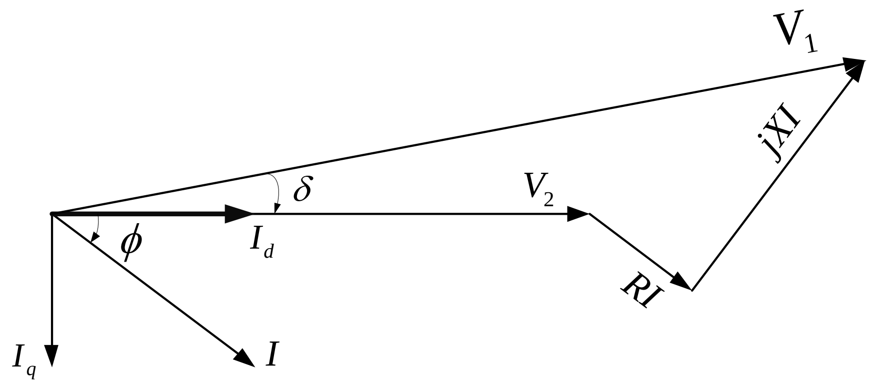

Fig. 2.2 Phasor diagram of transmission system without compensation

and also the drop in the transmission line will increase. This will lead to a drop in the load voltage V_2 and hence a poor voltage regulation as well as poor power factor as seen from source side.

2.2 Transmission System with Series Compensation

Figure 2.3 shows ideal series compensator connected between bus-i and bus-j of the system given in Fig. 2.1. Assume that the compensator exchanges only reactive power with the transmission line. In Fig. 2.3; i, j are the source and load buses, $V_1\angle\delta$ is the source voltage, $V_2\angle 0$ is the load voltage, $R + jX$ is the impedance of the transmission line and $I\angle\phi$ is the current passing through the transmission line. The phasor diagram,

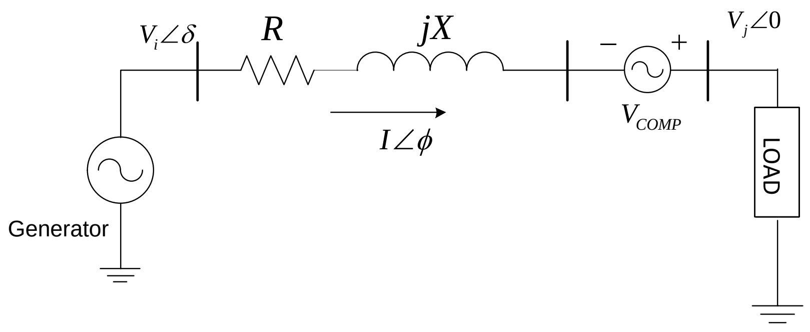

Fig. 2.3 Transmission system with series compensation

corresponding to the system shown in Fig. 2.3, is shown in Fig. 2.4. Series compensator introduces a capacitive voltage drop in the transmission line, which is in quadrature with the line current I as shown in Fig. 2.4. The amount of reactive power drop in the

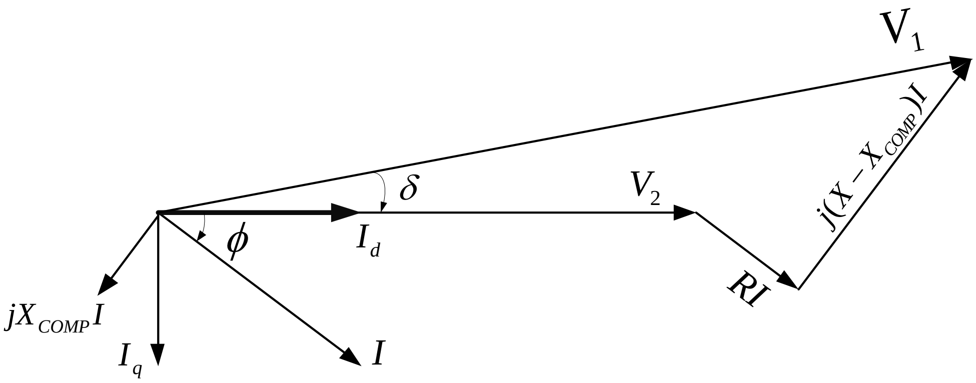

Fig. 2.4 Phasor diagram of transmission system with series compensation

transmission line is reduced from I^2X to $I^2(X - X_{COMP})$ due to the addition of series compensator. It can be observed from the phasor diagram that, as the capacitive voltage increases in the line, the total voltage drop in the transmission line gradually reduces. Thus the injection of reactive power leads to improvement of voltage profile in the system [8].

2.2.1 Power Transfer Capability Enhancement with Series Controller

Consider the system given in Fig. 2.1 but with series capacitance which is connected in series with the transmission line as shown in Fig. 2.5. In Fig. 2.5 source voltage is

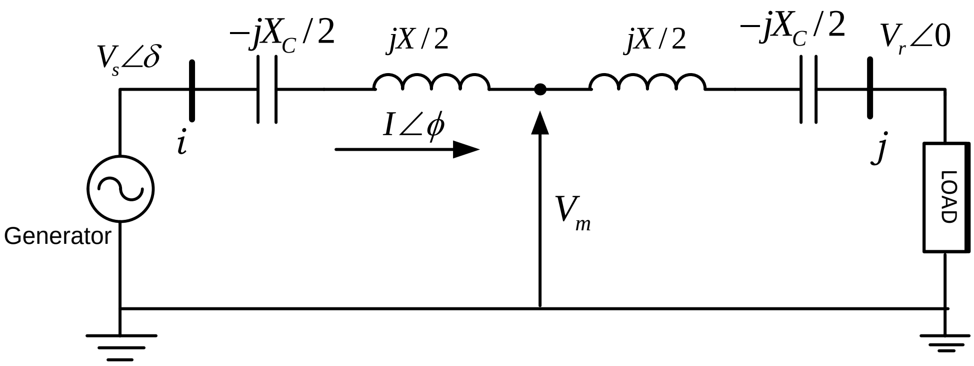

Fig. 2.5 Transmission system model with series compensation

represented by the voltage source $V_s\angle\delta$, $V_r\angle 0$ is the load voltage, V_m is the midpoint voltage and $I\angle\phi$ is the current passing through the transmission line. X is the total reactance of the line and resistance of line is neglected. The basic idea behind series compensation is to decrease the overall effective series impedance of transmission line and this series compensator is represented by two ideal capacitive reactances of value $X_c/2$ each, which is placed in series with the transmission line as shown above. The effective transmission line reactance X_{eff} after including the the series compensator is given in following equations.

$$X_{eff} = X - X_c \tag{2.1}$$

or

$$X_{eff} = (1-k)X \tag{2.2}$$

where k is the degree of series compensation, i. e.,

$$k = \frac{X_c}{X} \tag{2.3}$$

where, X and X_c are the reactance of transmission line and reactance of the series compensator, respectively. Assuming the magnitude of the sending end and receiving end voltages are equal, The relation ship between the voltages V_s, V_r, V_m and the transmission line current I after introducing the series compensator is represented in phasor diagram shown in Fig. 2.6.

Assume V_{line}, is the total voltage drop across the transmission line before compensation, the value of V_{line} is decreased by amount V_c by introducing the series compensator. The series compensator introduces a voltage V_c in the transmission line which is out of phase with the line voltage V_{line}, there by reducing the total reactive voltage drop which leads to improvement of power transfer from source to load. The real power P and reactive power Q transmitted from source to the load without and with series compensator are given by equations 2.4 to 2.5. The total reactive power injected by the series

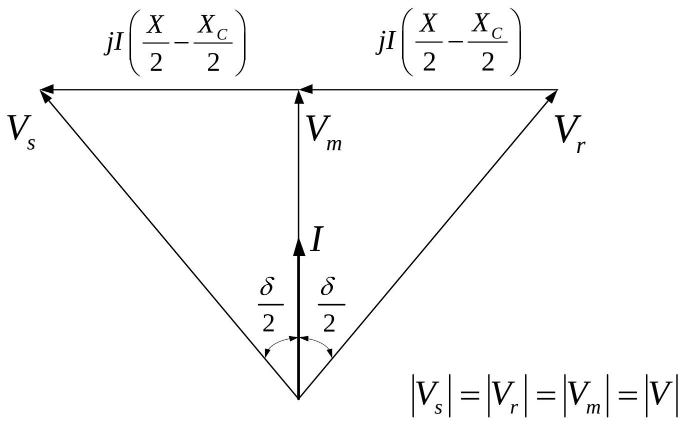

Fig. 2.6 Phasor diagram with series compensation

compensator is given by Q_c and given in 2.6.

$$P = \frac{V^2}{X} sin\delta \tag{2.4}$$

$$Q = \frac{V^2}{X}(1 - cos\delta) \tag{2.5}$$

$$Q_c = \frac{2V^2}{X}\frac{k}{(1-k)^2}(1 - cos\delta) \tag{2.6}$$

Where, δ is the angle between V_s and V_r. It can be easily observed from the above equations that, the magnitude of real power transfer from source to the load depends on the degree of compensation. As the value of k lies between 0 and 1, the magnitude of the real power transferred will always be greater than P_{max}. Where, P_{max} is the peak value of the power transferred without compensation. Fig. 2.7 represents the power versus angle characteristics of the transmission system with compensation i.e. the relation between active and reactive powers supplied from source to load with different degree of compensation k.

P, Q_c are real power supplied by the source and the reactive power supplied by the compensator. δ is the angle between source and load voltages, and k is the degree of compensation. In Fig. 2.7, $k = 0$ curves corresponding to the system without compensation. $k = 0.2$ and $k = 0.4$ curves represents the system with series compensation with degree of compensation 0.2 and 0.4. It can be observed from power-angle characteristics that series compensation can significantly increase the transmittable power at the expense

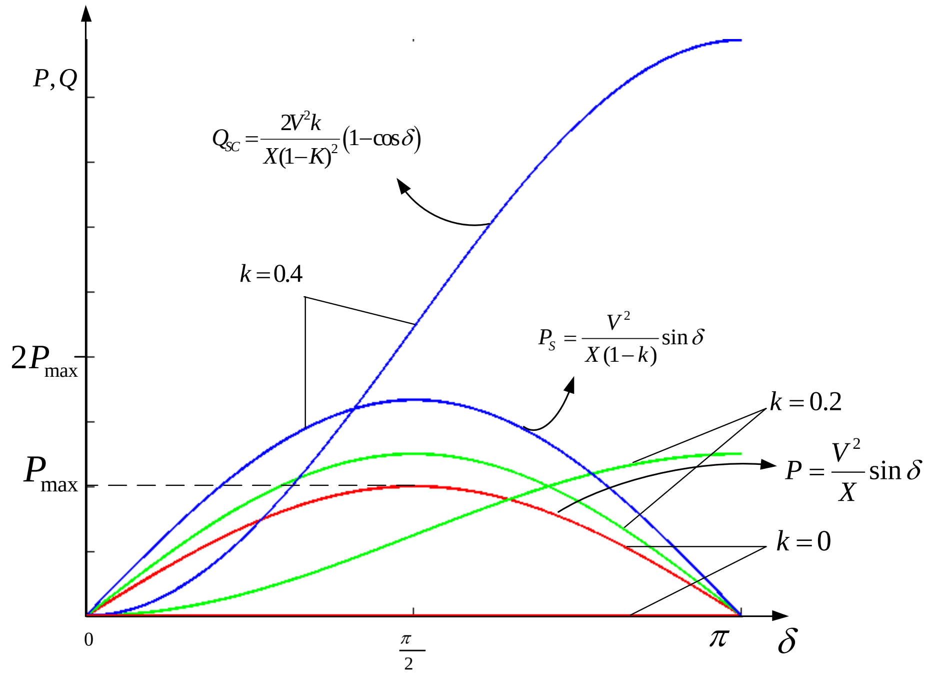

Fig. 2.7 Real power and reactive power vs. angle characteristics with series compensation

of a rapidly increasing reactive power demand in the transmission line [8].

Power electronics based power flow controllers like TCSC, increases the current in the given series impedance of the transmission line (and thereby the corresponding transmitted power) and voltage across the line by producing a voltage opposite to the prevailing voltage across the series line. In the present work the series compensating devices, TCSC is used to enhance the power transfer capability. The steady state modeling and operating characteristics of thyristor controlled series compensator is explained in the next section.

2.3 Principle of Operation and Modeling of TCSC

The basic Thyristor-Controlled Series Capacitor scheme was proposed in 1986 by Vithayathil as a method of "rapid adjustment of network impedance" [1] [3] . Fig. 2.8 represents the basic TCSC connected in series with a transmission line connected between the two buses j and k. R, X are the resistance and reactance of the transmission line. The TCSC configurations uses thyristor-controller reactors (TCR) in parallel with segments of a capacitor bank. The currents passing through the capacitor and TCR circuits in terms of delay angle α are represented by $i_c(\alpha)$ and $i_{TCR}(\alpha)$, respectively and i is the current in the transmission line.The working of TCR is briefly explained below.

2.3.1 Principle of operation of TCR

The Thyristor controlled reactor comprises a linear reactor, connected in series with a thyristor valve configuration as shown in the Fig. 2.8. The variation of current is obtained by control of the gate firing instant of the thyristors and thus of the conduction duration in each half cycle from a 90° firing angle delay as measured from the applied voltage zero for continuous conduction, to 180° delay for minimum conduction .

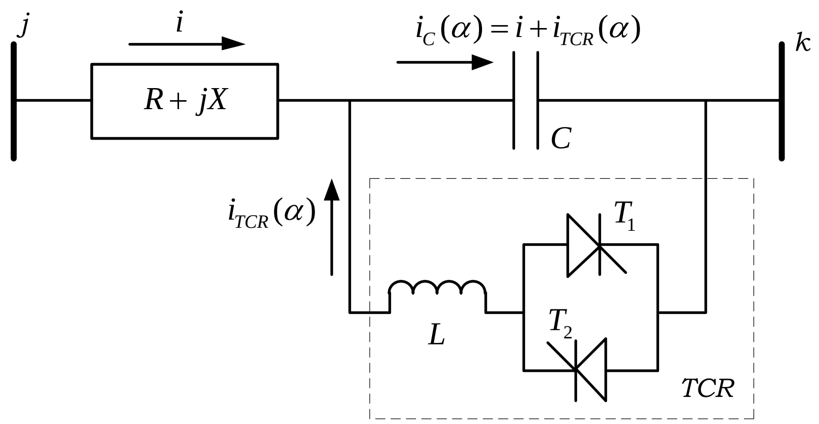

Fig. 2.8 Schematic diagram of TCSC

Figure 2.8 shows the schematic diagram TCR. The thyristors T_1 and T_2 forms a bidirectional thyristor valve. Thyristor valve can be brought into conduction by simultaneous application of a gate pulses to the thyristors T_1 and T_2. $v(t)$ is the voltage applied across TCR and $i(t)$ is the the current passing through the circuit and α is the delay angle. The valve will automatically come to blocking mode immediately after the ac current $i(t)$ crosses zero, unless the gate signal is applied. The current in the reactor can be controlled from maximum (thyristor valve closed) to zero (Thyristor valve open) by the method of firing delay angle (α) control. The closure of the thyristor valve is delayed with respect to the peak of the applied voltage in each half-cycle, and thus the duration of the current conduction intervals is controlled. Thus the total inductive reactance offered by the TCR varies according to the control strategies of the thyristor valve. The voltage across and current passing through the TCR in terms of delay angle (α) and conduction angle (σ) can be expressed as follows.

$$v(t) = V_m cos(\omega t) \tag{2.7}$$

$$i_L(t) = \frac{1}{L}\int_{\alpha}^{\omega t} v(t)\,dt = \frac{V_m}{\omega L}(sin(\omega t) - sin(\alpha)) \tag{2.8}$$

where V_m is the peak amplitude of the applied ac voltage, L is the inductance of the thyristor controlled reactor, and ω is the angular frequency of the applied voltage. It is evident from the equation 2.9 that the magnitude of the current $i_L(t)$ in the TCR can be varied continuously by the method of delay angle control from maximum value to zero. The amplitude $i_{LF}(\alpha)$ of the fundamental component of the reactor current is given by the equation 2.10. TCR can control the fundamental current continuously from zero (valve open) to a maximum (valve closed) as a variable reactive admittance. The value of the reactive admittance of TCR, $B_{TCR}(\alpha)$ as a function of delay angle α, at fundamental frequency is given in (2.17).

$$i_{LF}(\alpha) = \frac{V_m}{\omega L}\left(1 - \frac{2}{\pi}\alpha - \frac{1}{\pi}sin(2\alpha)\right) \tag{2.9}$$

$$B_{TCR}(\alpha) = \frac{1}{\omega L}\left(1 - \frac{2}{\pi}\alpha - \frac{1}{\pi}sin(2\alpha)\right) \tag{2.10}$$

2.3.2 Principle of operation of TCSC

The main circuit of the TCSC consists of a capacitor and a thyristor controlled inductive branch connected in parallel as shown in Fig. 2.8. The characteristic of the TCSC main circuit depends on the relative reactances of the capacitor bank $X_c = -\frac{1}{\omega_n C}$ and the thyristor branch $X_v = \omega_n L$. In general the reactance of the inductor is much smaller than that of the capacitor bank at rated frequency. In practice a boost factor, K_B, is defined as the quotient between the apparent and the physical reactance of the capacitor connected in TCSC.

$$K_B = \frac{X_{app}}{X_C} \tag{2.11}$$

The TCSC can operate in mainly three modes which exhibit different values of apparent reactance [3].

- Blocking mode
- Bypass mode
- Vernier mode

Blocking mode of operation

Blocking mode is operated when thyristor valve is not triggered and the thyristors are kept in non-conducting state. The line current passes only through capacitor. In this mode, the TCSC performs like a fixed series capacitor with boost factor equal to one. The resulting voltage in the steady state across the TCSC is given by:

$$V_{TCSC} = jX_C I \qquad X_C < 0 \tag{2.12}$$

Bypass mode of operation

If the thyristor valve is triggered continuously the valve stays conducting all the time and the TCSC behaves like a parallel connection of the series capacitor with thyristor controlled inducatnce valve. The resulting voltage in the steady state across the TCSC is given by:

$$V_{TCSC} = \frac{jX_L X_C}{X_L + X_C} I \qquad X_C < 0 \tag{2.13}$$

This voltage is inductive and the boost factor is negative. Therefore the bypass mode is utilized as a means to reduce the capacitor stress during faults.

Vernier mode of operation

If the thyristor valve is triggered with appropriate time gate pulse, the valve stays conducting for some time and for remaining time it will remain in non-conducting state. Here X_{TCR} is varied and hence X_{TCSC} also varies with its value depending on the gate pulse applied. The resulting voltage in the steady state across the TCSC is given by:

$$V_{TCSC} = \frac{jX_{TCR} X_C}{X_{TCR} + X_C} I \qquad X_C < 0 \tag{2.14}$$

2.3.3 Modeling of TCSC

A TCSC can be modeled as a variable reactance. The general block diagram of TCSC model is shown in Fig. 2.9. Based on a control strategy a reference reactance X_{ref}^{TCSC} is

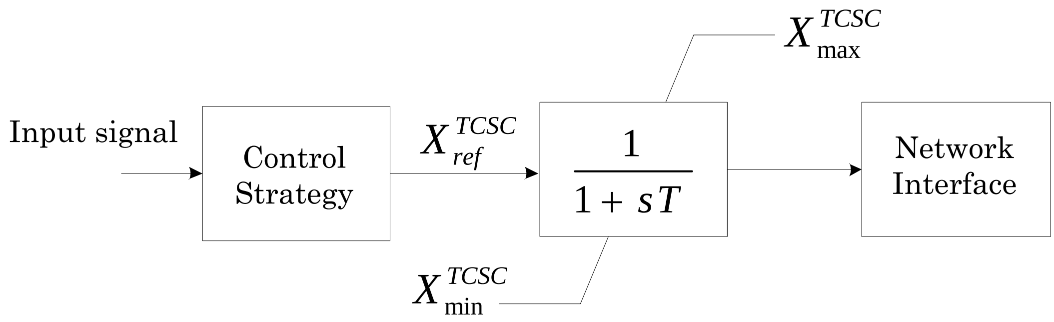

Fig. 2.9 Model of TCSC

determined. This signal is passed through a delay block. The time constant T approximates the delay due to the main circuit characteristics and control systems. The output of model is restricted by two limits:

1. Static reactance limit
2. Dynamic reactance limit

Static reactance limit is suggested by the planner for a desirable level of TCSC contribution. Dynamic reactance limit is a constraint, which is decided by the voltage across TCSC. It means that whenever the voltage across the TCSC exceeds the maximum permissible value V_{max}^{TCSC}, the reactance should be lowered. If I_{line} is the line current, then:

$$X^{TCSC} \leq \frac{V_{max}^{TCSC}}{I_{line}} \tag{2.15}$$

Mathematically, the TCSC reactance is modeled as:

$$X_{min}^{TCSC} \leq X_{TCSC} \leq X_{max}^{TCSC} \tag{2.16}$$

2.4 Summary

This chapter gives a brief introduction about the transmission system with and without series compensation. Power transfer capability enhancement with ideal series compensator are explained. The steady state modeling and principle of operation of thyristor controlled series capacitor (TCSC) is explained in detail.

CHAPTER 3

MAXIMIZING TTC OF A SYSTEM THROUGH OPTIMAL PLACEMENT OF MULTIPLE TCSC USING PSO

In the present work multiple number of TCSC are optimally placed to maximize the Total Transfer Capability (TTC) [9] or loadability with minimum investment cost. This optimization is solved using Particle Swarm Optimization (PSO) technique which will be discussed in this chapter. The main objective is to get the optimal number, location, rating of the multiple TCSC devices to be in the system to maximize TTC with minimum cost without violating the system constraints like power balance, voltage limits, reactive power limits of generator bus, thermal limit of lines and compensating device control parameter constraints using Particle Swarm Optimization (PSO) technique [7].

3.1 Total Transfer Capability Definitions and Determination

Transfer capability of a interconnected electric power system is defined as the maximum amount of power that can be transferred reliably from generation stations to the load centers without violating the system operating conditions. According to the report approved by NERC [4] the definitions of total transfer capability and available transfer capability are as following.

Total Transfer Capability (TTC): It is defined as the quantity of electric power that can be transferred over the interconnected transmission path reliably without violating the predefined set of conditions of the system.

Transmission Reliability Margin (TRM): It is defined as that amount of transmission transfer capability necessary to ensure that the interconnected transmission network is secure under a reasonable range of uncertainties in system conditions.

Capacity Benefit Margin (CBM): It is defined as that amount of transmission transfer capability reserved by load serving entities to ensure access to generation from interconnected systems to meet generation reliability requirements.

Available Transfer Capability (ATC): It is a measure of the transfer capability remaining in the physical transmission network for further commercial activity over and above already committed uses. Mathematically, ATC is defined as the Total Transfer Capability (TTC) less the Transmission Reliability Margin (TRM), less the sum of existing transmission commitments (which includes retail customer service) and the Capacity Benefit Margin (CBM).

$$ATC = TTC - TRM - CBM \tag{3.1}$$

TTC is an important parameter that indicates how much power transfer can take place without compromising the system security. The main reasons to calculate the total transfer capability are given below.

- Estimation of TTC can be used as a rough indicator of system stability
- TTC can be used for comparing the relative merits of planned transmission betterment
- To improve reliability and economic efficiency of the power markets
- For providing a quantitative basis for assessing transmission reservations to facilitate energy markets

The determination of transfer capability is generally based on the operation of the interconnected transmission network under a specific set of assumed operating conditions [10] and they are explained as following.

- System Conditions: Base case system operating conditions should be identified and modeled for the period to be analyzed, including projected customer demands, generation dispatch, system configuration, and base scheduled transfers, because as the system conditions change, the base case conditions of the system under which TTC is calculated may also need to be modified.
- Critical Contingencies: The generation and transmission contingencies through out the network should be evaluated to determine which facility outages are most restrictive to the total transfer capability analysis. The types of contingencies are consisted with individual system, power pool, regional and sub regional planning criteria.

- System Limits: The total transfer capability of the transmitted network is limited by the physical and electrical characteristics of the system, i.e thermal, voltage and stability limits of the system. As the system operating conditions vary, the restrictive limit for TTC calculation will vary as shown in Fig. 3.1. Fig. 3.1 shows the TTC calculation from region A to region B under stability limits, voltage limits and thermal limits with the variation of time. Different system limits for TTC calculation are briefly defined as following.

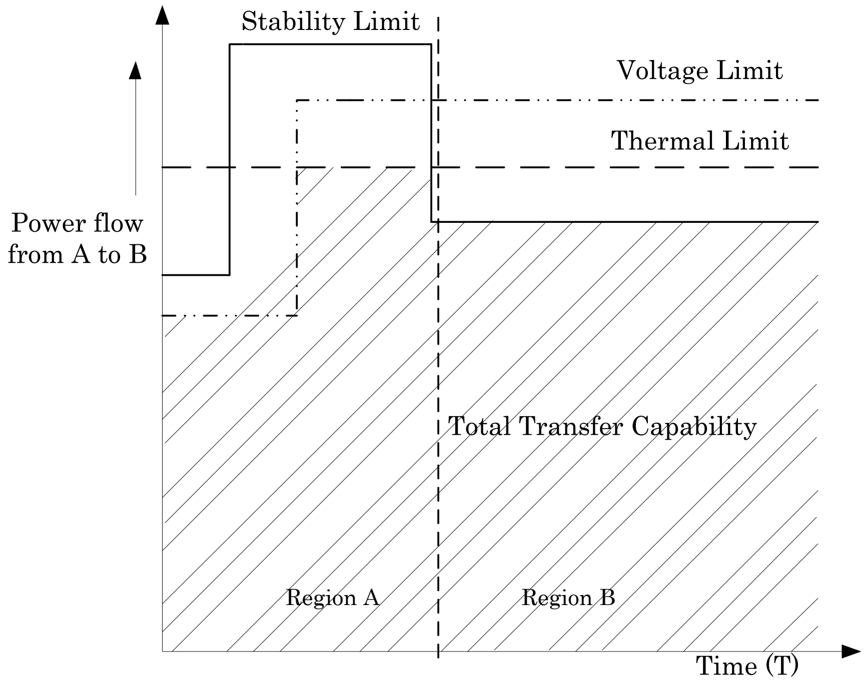

Fig. 3.1 Limits of total transfer capability

Thermal limit is the maximum amount of electrical current (power) that a transmission line can conduct over a specified time period before it sustains permanent damage by over heating or before it violates the public safety requirements.

Voltage limits are the system voltage limits at the buses, which must be maintained within the range of acceptable minimum and maximum limits to transfer the maximum amount of electric power without causing damage to the electric system or customer facilities.

Stability limit for the transmission network is the ability to survive the disturbances through the transient and dynamic time periods (from milliseconds to several minutes) following the disturbance. All generators that are connected to interconnected transmission systems must operate in synchronism with each other at the nominal frequency i.e. 50 Hertz. To stabilize the system, the oscillations must diminish as the electric system attain a new stable operating point. If the new stable operating point is not quickly established, the generators will likely lose synchronism with each other and a portion of the interconnected system will become unstable. In the present work repeated power flow method is used to calculate the transfer capability and explained in detail next.

3.1.1 TTC Calculation using Repeated Power Flow method

Repeated power flow approach starts from a base case, and repeatedly solves the power flow equations each time increasing the power transfer by a small increment until an operating limit is reached. The advantage of this approach is its simple implementation and the ease to take security constraints into consideration. In this dissertation, this method is adopted to solve TTC problem.

The Algorithm for repeated power flow method

In this work, the repeated power flow (RPF) method is used for the calculation of transfer capabilities due to the ease of implementation. This method involves the solution of a base case, which are the initial system conditions, and then increasing the transfer. After each increase, another load flow is solved and the security constraints tested. The computational procedure of this approach is as follows:

1. Establish and solve load flow for a base case
2. Check for system limits (bus voltage and line flow limits)
3. If the system constraints are not violated, increase the load by step size and repeat the load flow till the system constraints are violated.
4. If the system constraints are violated, decrease the load by step size and repeat the load flow till the system satisfies the constraints.
5. The limiting case gives the TTC of the system.

3.2 Optimal Placement of TCSC - Problem Formulation

To achieve the best utilization of the existing transmission systems, TCSC device should be installed in such a place to maximize the system loadability as much as possible, while satisfying the thermal limits of the transmission lines and the bus voltage limits in the network. But, since the cost of installing FACTS devices in general and TCSC in particular is too high, therefore, the objective function in this work is developed in such a way to find a compromise solution to this problem. As commonly done in multi-criteria constrained optimization, the problem is transformed into a single objective optimization problem.

3.2.1 Objective function formulation

The objective function here is defined as a summation of two terms [11]. One, the cost of FACTS device used i.e, the cost of TCSC which depends on the number of TCSC used. It also depends on the operating range of TCSC i.e, the rating of TCSC used in the transmission line. Second term depends on the thermal violation of all the lines in the system and bus voltage violation. There is a penalty factor introduced to penalize the objective function in order to keep the line flows of all the lines and the bus voltages within their limits. Now in this optimization problem we try to minimize the cost and also the penalty for flow violations and bus voltage violation. That is we try to minimize the whole objective function value. Thus the objective function formed will be as below [11]:

$$Minimize\ \ F = 1000 \times C_{TCSC} \times s + \lambda_1 \times VL \tag{3.2}$$

Where:
F is the objective function;
C_{TCSC} is the cost of TCSC device (per Var);
s is the operating range of TCSC;
λ_1 is penalty factor used to penalize the objective function in order to keep the line flows and the bus voltage within their limits;
VL is thermal and bus voltage violation limits factor.
In the first term of the objective function, C_{TCSC} presents the installation cost of TCSC device in the network, which is given in the following equation.

$$C_{TCSC} = 0.0015s^2 - 0.7130s + 153.75 \tag{3.3}$$

In the second term of the objective function, VL is defined as penalty factor introduced in order to keep the line flows of all the lines and the bus voltages within their limits. VL is defined in the following equation:

$$VL = \sum_{i=1}^{ntl} OLL + \sum_{j=1}^{nb} BVV \tag{3.4}$$

where: OLL is the over loaded line factor;

BVV is the bus voltage violation factor;

ntl is the number of lines in the network; and

nb is the number of buses in the network.

In the equation (3.4) the values of OLL and BVV is calculated with the following constraints:

$$OLL = \begin{cases} 0, & if \quad P_{ij} \leq P_{ij}^{max} \\ log\left(\Gamma_{OLL} \times \left(P_{ij}/P_{ij}^{max}\right)\right) & if \quad P_{ij} > P_{ij}^{max} \end{cases} \tag{3.5}$$

$$BVV = \begin{cases} 0, & if \quad 0.9 \leq V_b \leq 1.1 \\ log\left(\Gamma_{BVV} \times (abs\ (1 - V_b) - 0.1)\right) & else \end{cases} \tag{3.6}$$

Where:

Pij is the real power flow between buses i and j ;

P_{ij}^{max} is the thermal limit for the line between buses i and j ;

V_b is the voltage at bus b ; and

Γ_{OLL} and Γ_{BVV} are respectively two coefficients used to adjust the slope of the logarithm.

OLL is the over loaded line factor used to penalized the overload lines and it is computed for every line in the network. The value of OLL is equal to 0 when the line loading is equal or less than 100%, otherwise the value of OLL increases logarithmly (natural logarithm) with the overload.

BVV Factor in equation (3.6), concerns voltage levels, and it is calculated for all buses in the network. The value of BVV is equal to 0 for voltage levels between 0.90 and 1.1, and outside this range its value increases logarithmly with voltage violation.

3.3 Particle Swarm Optimization (PSO)

Several stochastic search techniques, such as Genetic Algorithm (GA) [6], Particle Swarm Optimization (PSO) [7], and Simulated Annealing (SA) [12], were developed to solve global combinatorial optimization problems, and were widely applied to several optimization problems in different research areas. These techniques have found a general acceptance in many applications, because of their capability of finding the global optimal solution to the optimization problem they solve, and they don't suffer from the extant computational complexity and other limiting mathematical assumptions that the traditional optimization techniques suffered from.

Here particle swarm technique is proposed for the optimization problem under consideration, and the proposed technique is applied as follows:

3.3.1 Description of the implemented particle swarm optimization technique

Particle Swarm Optimization (PSO) is a stochastic global optimization approach, and its main strength is in its simplicity and fast convergence rates. PSO is distinctly different from other evolutionary-type methods in that it does not use the filtering operation (such as crossover and/or mutation). Unlike Genetic Algorithm (GA) and other heuristic algorithms, PSO has the flexibility to control the balance between the global and local exploration of the search space. This unique feature of PSO overcomes the premature convergence problem and enhances the search capability. Also it is unlike the other methods, the solution quality does not rely on the initial population. Starting anywhere in the search space, the PSO algorithm ensures the convergence to the optimal solution.

In PSO algorithm, each member is called 'particle', and each particle flies around in the multi-dimensional search space with a velocity, which is constantly updated by the particle's own experience and the experience of the particle's neighbors. PSO is based on the exchange of information between individuals, so called *particles*, of the population, so called *swarm*. Each particle adjusts its own position towards its previous experience and towards the best previous position obtained in the swarm. Memorizing its best own position establishes the particle's experience implying a local search along with global search emerging from the neighboring experience or the experience of the whole swarm. Two variants of the PSO algorithm were developed, one with a global neighborhood, and other one with a local neighborhood. According to the global neighborhood, each particle moves towards its best previous position and towards the best particle in the whole swarm, called g_{best} model. On the other hand, according to the local variant, called l_{best} model, each particle moves towards its best previous position and towards the best particle in its restricted neighborhood. Here, global variant with binary version is applied to find the optimal location of multiple TCSC to be placed in transmission lines. In a PSO algorithm, population is initiated randomly with particles and evaluated to compute finesses together with finding the particle best (best value of each individual so far) and global best (best particle in the whole swarm). Initially, each individual with its dimensions and fitness value is assigned to its particle best. The best individual among particle best population, with its dimension and fitness value is, on the other hand, assigned to the global best. Then a loop starts to converge to an optimum solution. In the loop, particle and global bests are determined to update the velocity first. Then the current position of each particle is updated with the current velocity. Evaluation is again performed to compute the fitness of the particles in the swarm. This loop is terminated with a stopping criterion like limit on maximum number of generations that can be produced.

The basic elements of PSO algorithm is summarized as follows:

- $Particle$: $X_i^k$is a candidate solution i in swarm at iteration k. The i^{th} particle of the swarm is represented by a d-dimensional vector and can be defined as $X_i^k = \left[x_{i1}^k, x_{i2}^k, \ldots.., x_{id}^k\right]$, where, $x_{ip} \in [l_p, u_p\,]$, $p \in [1,d]$. l_p and u_p are the lower and upper bounds for p^{th} dimension respectively. Here all x are the optimized parameters and x_{id}^k, is the position of the i^{th} particle with respect to d^{th} dimension. In other words, it is the value d^{th} optimized parameter in the i^{th} candidate solution.

- $Population$: pop^k is the set of n particles in the swarm at iteration k, i.e. $pop^k = \left[X_1^k, X_2^k, \ldots.., X_n^k\right]$

- $Particle\ velocity$: V_i^k is the velocity of particle i at iteration k. It can be described as $V_i^k = \left[v_{i1}^k, v_{i2}^k, \ldots.., v_{id}^k\right]$, where v_{id}^k is the velocity with respect to d^{th} dimension. Velocity is clamped to a maximum velocity $V_{max} = [v_{max1}, v_{max2}, \ldots.., v_{maxd}]$ which is specified by the user.

- $Particle\ best$: $PB_i^k$is the best value of the particle i obtained until iteration k. The best position associated with the best fitness value of the particle i obtained so far is called particle best (P_{best}) and defined as $PB_i^k = \left[pb_{i1}^k, pb_{i2}^k, \ldots.., pb_{id}^k\right]$ with the fitness function $f\left(PB_i^k\right)$

- *Global best* : GB^k (g_{best}) is the best position among all particles in the swarm, which is achieved so far and can be expressed as $GB^k = \left[gb_1^k, gb_2^k, \ldots.., gb_d^k\right]$ with the fitness function $f\left(GB^k\right)$

- *Termination criterion* : it is a condition that the search process will be terminated. In this study, search is terminated when the number of iteration reaches a predetermined value, called maximum number of iteration.

In this work, the implemented PSO technique can be described as follows [11]:

- Step I: Initialize related parameters, such as the size of swarm m , the maximum number of iteration n , the number of variables to be optimized, the load factor, and the power flow data.

- Step II: an initial population is randomly generated to consider the variables that should be optimized (the number, the locations, and the parameter settings of multiple TCSCs) satisfying the following conditions: number of TCSC devices is in the range [1, ntl_{TCSC}] , candidate locations are in the range [1, ntl] , and the reactances range of TCSC devices.

  $$ntl_{TCSC} = ntl - ntl_T \tag{3.7}$$

  ntl_{TCSC} is the maximum number of the lines in the network that can be chosen to install the TCSC;
  ntl is the total number of lines in the network; and
  ntl_T is the number of lines in the network that contain transformers.
  Binary version of PSO is applied to find the optimal location of TCSC in transmission lines. So for this, the population of particles is constructed randomly. For each dimension of a particle, a binary value of 0 or 1 is assigned with a probability of 0.5. In particular,

  $$\begin{array}{l} if \quad U(0,1) > 0.5, \quad then \quad x_{id}^0 = 1 \\ else \quad x_{id}^0 = 0 \end{array}$$

  The reactances of the TCSC devices is randomly generated according to the working range of TCSC which is considered as follows:

  $$-0.8X_L \leq X_{TCSC} \leq 0.2X_L \qquad \text{p.u} \tag{3.8}$$

  Where:
  X_{TCSC} is the reactance added to the line by placing TCSC;
  X_L is the reactance of the line where TCSC is located.

- Step III: The fitness for each individual in the population is evaluated by taking the inverse of the objective function 3.2

- Step IV: a new population is created after updating the velocity by following equation.

  $$v_{id}^{n+1} = wv_{id}^n + c_1 r_1^n \left(P_{id}^n - x_{id}^n\right) + c_2 r_2^n \left(P_{gd}^n - x_{id}^n\right) \tag{3.9}$$
  $$x_{id}^{n+1} = x_{id}^n + v_{id}^{n+1} \tag{3.10}$$

Where:
$c1$ and $c2$ are two positive constants, called cognitive and social parameters respectively;
m is the size of the swarm;
D is the number of members in a particle;
$r1$ and $r2$, are random numbers, uniformly distributed in $[0,1]$;
n is the pointer of iterations (generations); and
w is the inertia weight, which provides a balance between global and local explorations.It is specified by equation

$$w = w_{max} - \frac{w_{max} - w_{min}}{itermax} \times iter \tag{3.11}$$

Where:
w_{max} is the initial weight;
w_{min} is the final weight;
$iter$ is the current iteration number; and
$iter_{max}$ is the maximum iteration number (generations).
In case of binary PSO for optimal locations, velocity values are restricted to some minimum and maximum values, namely $V_i^k = [V_{min}, V_{max}]$. The initial velocity i in the d^{th} dimension is established by $v_{id}^0 = V_{min} + (V_{max} - V_{min}) * rand()$. This limit enhances the local search exploration of problem space.
For finding new solutions we need to use two useful functions for generating new solutions, namely a sigmoid function to force velocity values to be inside the maximum and minimum allowable values. So whenever a velocity value is computed, the following piece-wise function, whose range is closed interval $[V_{max}, V_{min}]$, is used to restrict them to minimum and maximum value.

$$h\left(v_{id}^k\right) = \begin{cases} V_{max}, & if \quad v_{id}^k > V_{max} \\ v_{id}^k & if \quad \left|v_{id}^k\right| \leq V_{max} \\ V_{min}, & if \quad v_{id}^k < V_{min} \end{cases} \tag{3.12}$$

After applying the piece-wise linear function, the following sigmoid function is used to scale the velocities between 0 and 1, which is then used for converting them to the binary values. That is,

$$sigmoid\left(v_{id}^k\right) = \frac{1}{1 + e^{-v_{id}^k}} \tag{3.13}$$

So, new solutions are found by updating the velocity and dimension respectively. First, we compute the change in the velocity v_{id}^k such that

$$\Delta v_{id}^{k-1} = c_1 r_1 \left(pb_{id}^{k-1} - x_{id}^{k-1}\right) + c_2 r_2 \left(gb_d^{k-1} - x_{id}^{k-1}\right) \tag{3.14}$$

Then we update the velocity v_{id} by using the piece-wise linear function such that

$$v_{id}^k = h\left(v_{id}^{k-1} + \Delta v_{id}^{k-1}\right) \tag{3.15}$$

Finally we update the dimension d of the particle i such that

$$x_{id}^{k} = \begin{cases} 1, & if \;\; U\left(0,1\right) < sigmoid\left(v_{id}^{k}\right) \\ 0, & otherwise \end{cases} \tag{3.16}$$

- Step V: If the maximum number of iteration is reached, and the condition $VL = 0$ (this means that there is no thermal lines or bus voltage limitation violation) is still satisfied with the final best individual obtained (note that the final best individual and its corresponding load factor is stored), then the load factor is increased by 1% again from Step II, else the process continues to the next step.
- Step VI: stop the process, print the best individual and load factor.

PSO is very fast in converging to a solution when compared to genetic algorithms because of its mathematical simplicity. PSO is used to solve this optimization problem.

3.4 Summary

In this chapter we looked at basic transfer capability definitions. Determination of total transfer capability (TTC) with repeated power flow method is explained in detail. Particle swarm optimization method is explained to solve multi objective optimization problem consisting of maximization of TTC, simultaneously with minimum device investment cost without violating system operating constraints like line thermal limits, bus voltage limits, power balance constraints and device control parameter constraints. A flow chart for PSO algorithm is shown in Fig. 3.2

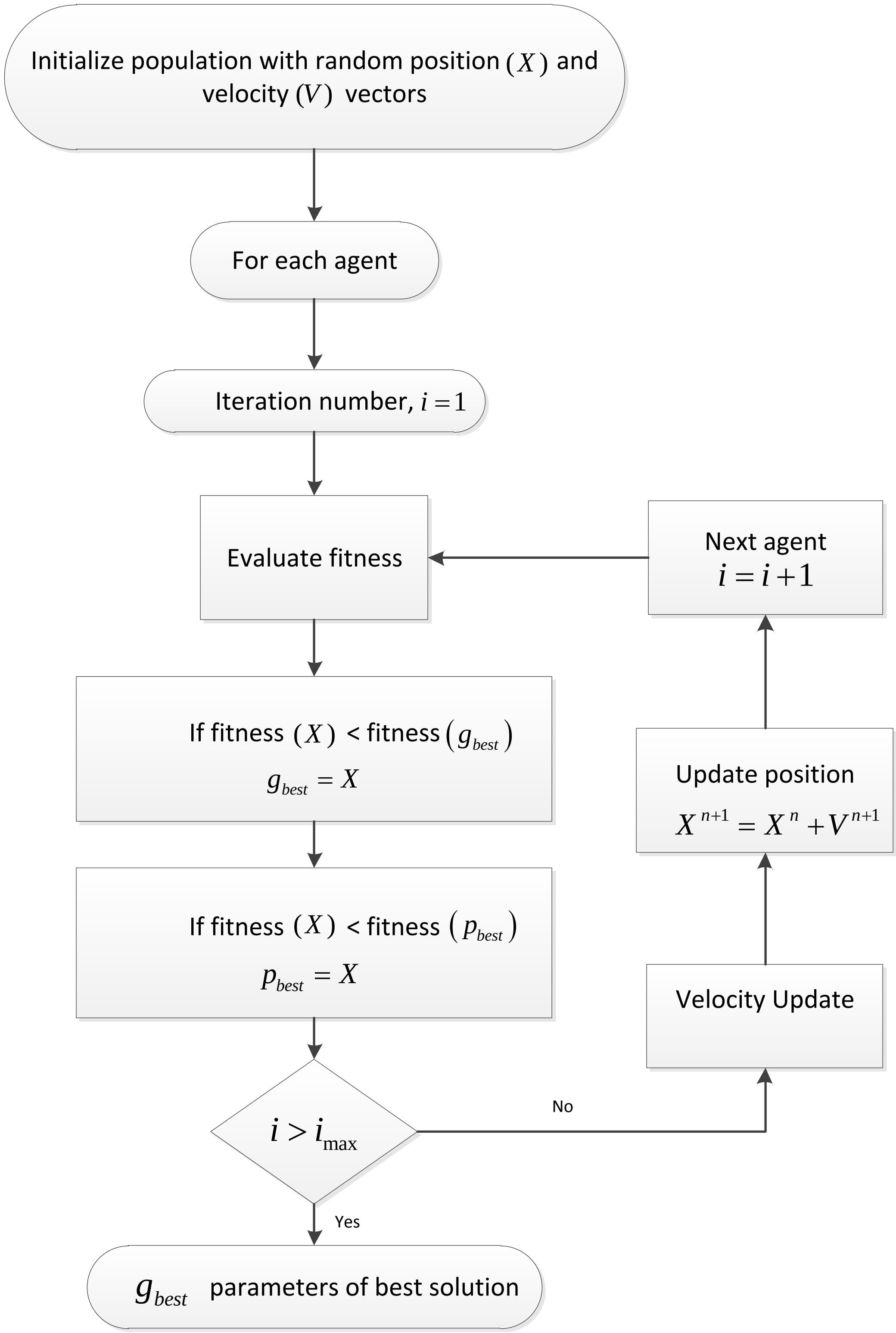

Fig. 3.2 Flowchart of PSO algorithm

CHAPTER 4

SIMULATION RESULTS

The proposed methodology, of optimally placing multiple TCSC to maximize TTC, has been applied to IEEE 6-BUS test system and IEEE 30-BUS test system. The IEEE 6-BUS and IEEE 30-BUS test system data is given in Appendix A and B, respectively. The method is applied in two stages. First stage is finding the total transfer capability without placing TCSC. Second stage is calculating the TTC with optimal number of TCSC placed in suitable locations with minimum rating, so as to minimize cost, without violating the operating system constraints. This optimization problem is solved using particle swarm optimization. There are three objectives for this optimization problem which is solved using PSO. The three objectives are as following:

1. Optimal number of TCSC
   - To find optimal number of TCSC devices to be used in the transmission lines using PSO. By reducing the number of TCSC devices the cost function is reduced.
2. Optimal location of TCSC
   - The TCSC devices used needs to be placed in suitable location in the system to get the maximum usage. This is solved using binary PSO
3. Optimal rating of TCSC
   - The optimal rating of TCSC devices is found using PSO.

4.1 Total TTC Calculation without TCSC

Repetitive Power Flow method was used, as explained in section 3.1 , to calculate the total transfer capability. To find TTC through repetitive power flow, we try to increase load in regular intervals until a limiting case has been reached where the line limit constraints or bus voltage constraints has been violated. The total load below that limiting case is TTC of the system.

$$TTC = \sum_{i=1}^{N_{PQ}} P_{Di\,max} \tag{4.1}$$

The TTC is computed by increasing load such that maximum load is reached as shown in equation (4.1) by implementing the algorithm in section 3.1.1. The results for the IEEE 6-BUS system and the IEEE 30-BUS system are given as following.

4.1.1 IEEE 6-BUS System

IEEE 6-BUS system has 6 buses of which 3 are generator buses, 3 are load buses. It has 11 transmission lines and no tap changing transformers or shunt reactors. Bus-1 is taken as the slack bus. The three generators are placed at buses 1, 2 and 3 respectively. For TTC calculation, the load is increased in steps of 0.01 $p.u$ untill the system contraints get violated. All the three loads are increased by same percentage from the base case. The power factor of the loads is taken constant.

4.1.2 IEEE 30-BUS System

IEEE 30-BUS system has 30 buses of which 6 are generator buses, 24 are load buses. It has 41 transmission lines and 4 tap changing transformers. Bus-1 is taken as the slack bus. The six generators are placed at buses 1, 2, 3, 4, 5 and 6, respectively. Four transformers with off-nominal tap ratio are placed in the lines between buses 6-9, 6-10, 4-12 and 27-28 and shunt reactors are placed at the buses 10, 12, 15, 17, 20, 21, 23, 24 and 29. Just like in case of IEEE 6-BUS system, the load is increased in steps of 0.001 $p.u$ from the based case, keeping power factor constant, till the voltage and line limit constraints are violated.

4.1.3 Transfer Capability without TCSC - results

Table 4.1 TTC values without TCSC (Base 100 MVA)

Test system	Bace case ($p.u$)	TTC ($p.u$)	Loadability increase w.r.t base case (%)
IEEE-6 BUS system	2.1	2.26	7.62
IEEE-30 BUS system	2.834	2.894	2.12

The calulated TTC is tabulated in Table 4.1 for both IEEE 6-BUS system and IEEE 30-BUS System, without TCSC in the system. It can be observed from the Table 4.1

that, IEEE 6-BUS system can deliver 226 MW and IEEE 30-BUS System can deliver maximum 289.4 MW of real power from genarating stations to all load centers without TCSC in the system, without violating the system constraints. So the Load can be increased up to 7.62% and 2.12% for IEEE 6-BUS system and IEEE 30-BUS system, respectively.

4.2 Total TTC Calculation with TCSC

The solution of the objective function given in (3.2), Chapter 3, will give the optimal number, location and rating of TCSC simultaneously. The equality and inequality constraints such as line limits and bus voltage violation are given in equation (3.5) and (3.6). For each case of load we find the optimal number, locations and ratings of TCSC. To find TTC with TCSC, we increase the load till any of the system constraints (bus voltage limit or line power limit) gets violated. We find the limiting case of total load where the voltage and line limit constraints are violated. The total load below the limiting case gives the loadability or TTC of the system. Table 4.2 gives the PSO parameters

Table 4.2 Parameter values for PSO

Parameter	Values
c_1, c_2	1.5
w_{max}	0.9
w_{min}	0.4
deviation of initial velocity	10
number of swarm beings	50
number of generations	100

used to minimize the objective function given in (3.2) with the constraints. The results for IEEE 6-BUS system and IEEE 30-BUS system are explained next.

4.2.1 IEEE 6-BUS System

Figure 4.1 shows the convergence of the objective function with respect to number of iterations using PSO algorithm. The objective function converges to a solution in about 30 iterations.

Table 4.3 shows the optimal location and rating of TCSC to be placed in the IEEE 6-

Table 4.3 TCSCS location and rating for IEEE 6-BUS System

Serial number	Location		Rating
	From Bus	To Bus	K_{TCSC}
1	1	4	-0.182
2	1	5	-0.227
3	2	4	-0.341
4	2	5	-0.501
5	2	6	-0.770
6	3	5	-0.152
7	3	6	-0.707

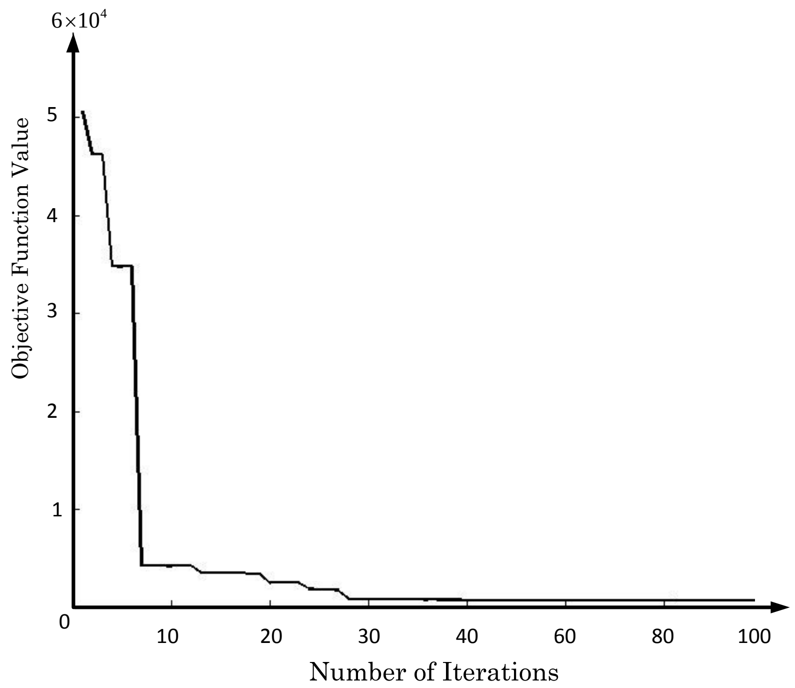

Fig. 4.1 Convergence of the Objective function, optimal placement of multiple TCSC using PSO, for IEEE 6-BUS system

BUS system. Table 4.5 shows the TTC for IEEE 6-BUS test system and IEEE 30-BUS test system after placing multiple TCSC. It can observed from the tables 4.5 and 4.3 that for IEEE 6-BUS test system the transmission capability has increase by placing 7 TCSC devices from 2.26 *p.u* to 2.553 *p.u*. So placing multiple TCSC optimally has increased the TTC by 12.96% with respect to the TTC of system without TCSC. The cost of installation of TCSC devices came out to be 683000 $.

Table 4.4   TCSC loccation and rating for IEEE 30-BUS System

Serial number	Location		Rating
	From Bus	To Bus	K_{TCSC}
1	15	23	-0.351

4.2.2 IEEE 30 BUS System

Figure 4.2 shows the convergence of the objective function versus number of iterations plot using PSO algorithm for 30 Bus System. The objective function converges to a solution in about 50 iterations

Table 4.4 shows the optimal location and rating of TCSC to be placed in the IEEE

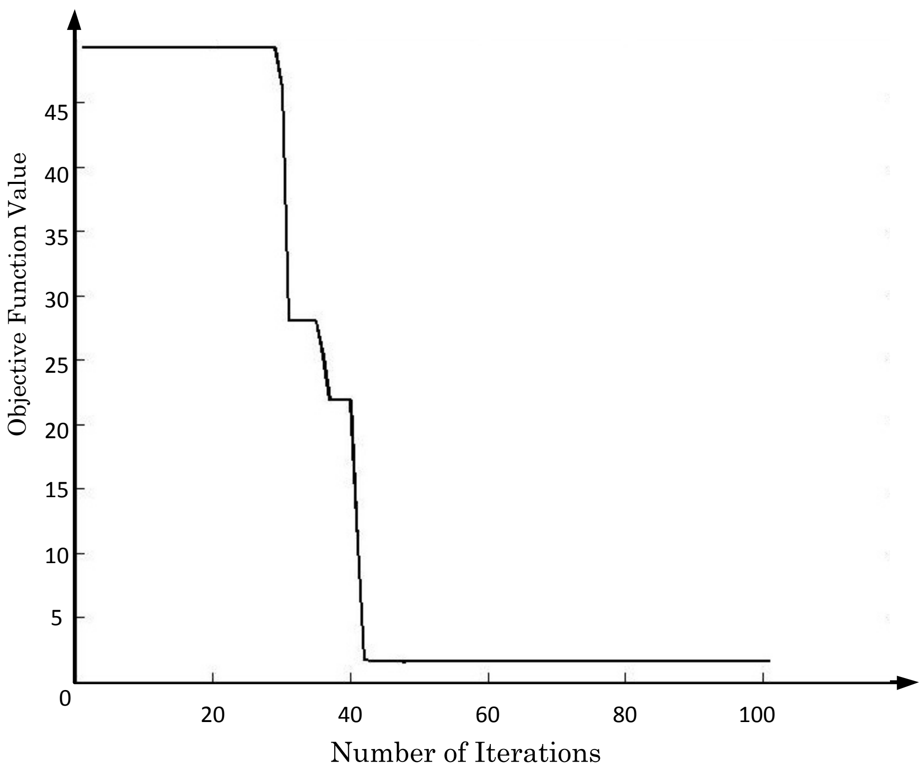

Fig. 4.2   Convergence of the Objective function, optimal placement of multiple TCSC using PSO, for IEEE 30-BUS system

30-BUS system. Tables 4.5 and 4.4 gives the TTC value for the IEEE 30-BUS test system after placing TCSC. It can be observed from the table that the transmission capability has increased by placing one TCSC device from 2.894 *p.u* to 2.954 *p.u*. So placing multiple TCSC optimmally has increased the TTC by 2% with respect to the TTC of system without TCSC. The cost of installation of that one TCSCS came out to be 19000$.

The results from the above two test systems clearly shows that the effectiveness of the proposed algorithm to maximize the TTC, simultaneously by optimally placing multiple TCSC.

Table 4.5 TTC results with TCSC for IEEE 6-BUS system and IEEE 30-BUS system

Test system	Base case $(p.u)$	TTC with TCSC	Loadability increase w.r.t base case (%)	Loadability increase w.r.t TTC without TCSC (%)
IEEE-6 BUS system	2.1	2.553	21.57	12.96
IEEE-30 BUS system	2.834	2.954	4.23	2.07

4.3 Summary

In this chapter the proposed method is applied to IEEE 6-BUS and IEEE 30-BUS system and the results are presented. The results are given in two stages, first stage TTC calculation without TCSC, and the second stage is TTC calculation with TCSC to maximize the TTC with minimum cost, without violating system constraints. The test results shows that the proposed method has effectively improved TTC with minimum investment cost.

CHAPTER 5

CONCLUSIONS

The loads in a typical power system vary continuously over a day in general and they are also subjected to variations caused by weather (ambient temperature) and other unpredictable factors. Thus, the power flow in transmission line can vary even under normal steady state conditions resulting in overloading of some lines and consequently voltage collapses at the buses due to shortage of reactive power. The required safe operating margin of transmission lines can be substantially improved through FACTS devices. The FACTS controllers can enable a line to carry power closer to its thermal rating and offers continuous control of power flow or voltage changes, against daily load changes by controlling the parameters that govern the operation of transmission systems like series impedance, shunt impedance, line current, bus voltage, load bus phase angle, and the damping of oscillations at various frequencies below the rated frequency.

TCSC, a series FACTS controller, has been used in the present work to improve the power transfer capability of the system under steady state condition. A multi-objective function has been proposed for finding the optimal number, place and rating of TCSC to maximize TTC. To solve this multi-objective problem of finding optimal number, location and rating of multiple TCSC, Particle Swarm Optimization algorithm has been used.

The proposed methodology, of optimally placing multiple TCSC to minimize cost and maximize TTC, simultaneously has been applied to sample 6-BUS test system and IEEE 30-BUS systems. It has been observed from the simulation results that, the proposed method of solving multi objective function improves the TTC significantly while maintaining the system constraints.

5.1 Scope for Future Work

The proposed methodology of formulating the multi-objective function consisting of placing optimal numbers of TCSC, in optimal locations with optimal ratings to maximize total transfer capability with minimum investment cost, can be applied to other

FACTS devices like Unified Power Flow Controller (UPFC), Interline Power Flow Controller (IPFC), Thyristor Controlled Voltage Regulator (TCVR) and Thyristor Controlled Phase Angle Regulator (TCPAR). This methodology can be extended for placing multiple number of multiple FACTS devices to get the optimal locations and optimal ratings of multiple FACTS decies to be used.

APPENDIX A

IEEE 6-BUS SYSTEM DATA

The single line diagram of the stranded IEEE 6-BUS system is shown in Fig. A.1. It consists of 3 generator buses, 3 load buses, 11 transmission lines and no tap changing transformers [13]. The bus data and line data are given in tables A.1 and A.2, respectively. The values given in tables are the $p.u$ values. In bus data table A.1 Q_{min} and Q_{max} are the minimum and maximum reactive power limits respectively, that can be supplied by the corresponding generator. The base power is 100 MVA and base voltage 400 V.

A.1 Single Line Diagram of IEEE 6-BUS System

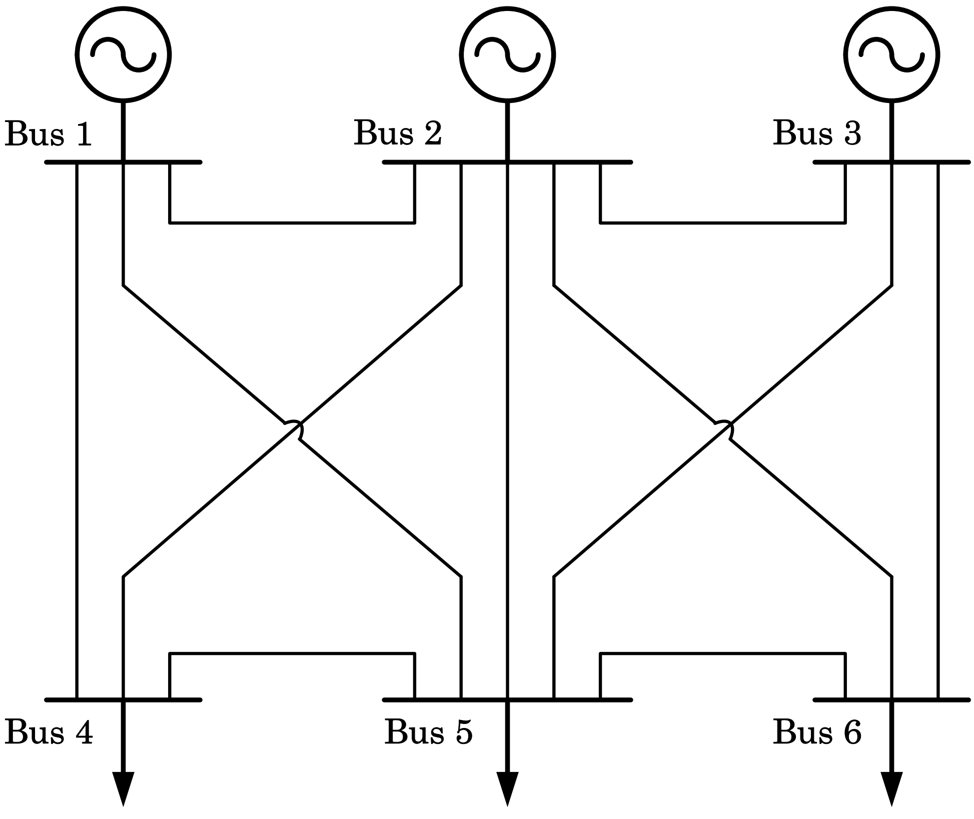

Fig. A.1 Single Line Diagram of IEEE 6-BUS System

A.2 Bus Data

Table A.1 Bus data for IEEE 6-BUS system

Bus number	Type	P_g	Q_g	P_d	Q_d	V_m	Q_{min}	Q_{max}	V_{min}	V_{max}
1	slack	0	0	0	0	1.05	–	–	0.9	1.1
2	PV	0.5	0	0	0	1.05	- 0.375	0.375	0.9	1.1
3	PV	0.6	0	0	0	1.07	- 0.45	0.45	0.9	1.1
4	PQ	0	0	0.7	0.7	1	–	–	0.9	1.1
5	PQ	0	0	0.7	0.7	1	–	–	0.9	1.1
6	PQ	0	0	0.7	0.7	1	–	–	0.9	1.1

A.3 Line Data

Table A.2 Line data for IEEE 6-BUS system

From Bus	To Bus	R	X	B
1	2	0.10	0.20	0.02
1	4	0.05	0.20	0.02
1	5	0.08	0.30	0.03
2	3	0.05	0.25	0.03
2	4	0.05	0.10	0.01
2	5	0.10	0.30	0.02
2	6	0.07	0.20	0.025
3	5	0.12	0.26	0.025
3	6	0.02	0.10	0.01
4	5	0.20	0.40	0.04
5	6	0.10	0.30	0.03

P_{max} for each line is calculated assuming that the system is loaded up to 70% for the base case as given above.

APPENDIX B

IEEE 30-BUS SYSTEM DATA

The single line diagram of the stranded IEEE 30-bUS system is shown in Fig. B.1. It consists of 6 generator buses, 24 load buses, 41 transmission lines and 4 tap changing transformers. The bust data and line data are given in tables B.1 and B.2, respectively. The values given in tables are the *p.u* values. Here in bus data table B.1 Q_{min} and Q_{max} are the minimum and maximum reactive power limits respectively, that can be generated by the corresponding generator. The base power is 100 *MVA* and base voltage 400 *V*.

B.1 Single Line Diagram of IEEE 30-BUS System

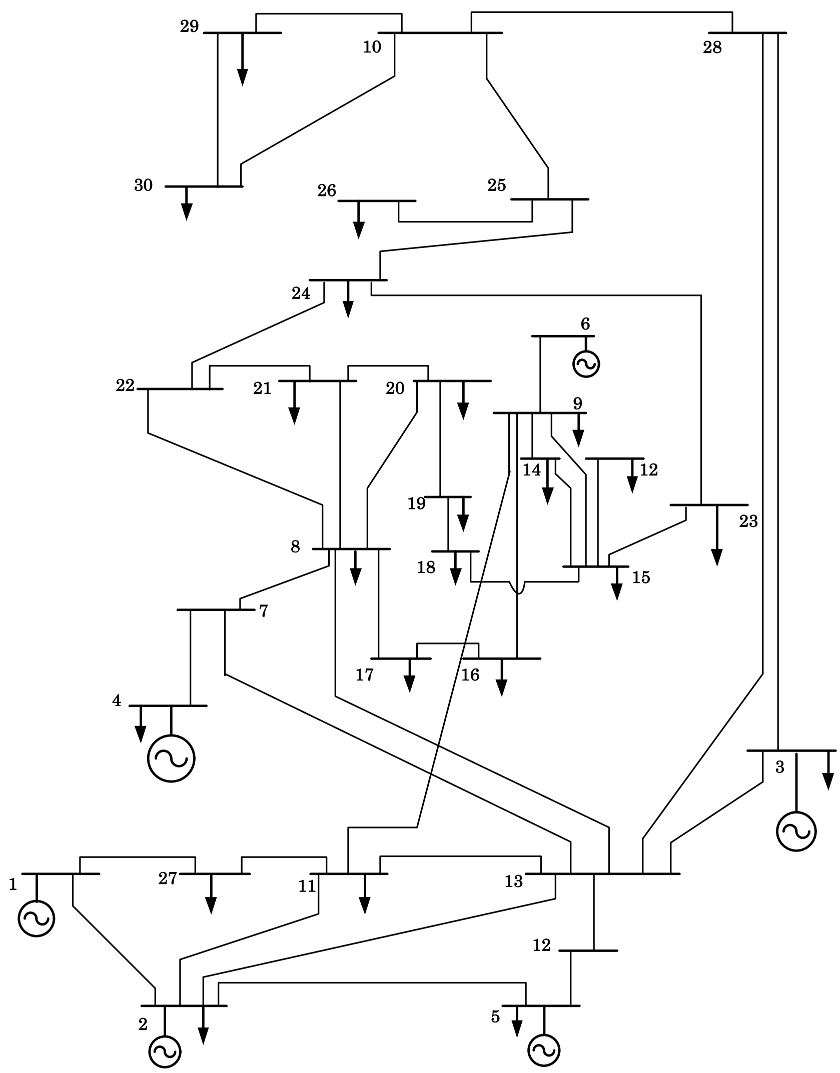

Fig. B.1 Single Line Diagram of IEEE 30-BUS System

B.2 Bus Data

Table B.1 Bus data for IEEE 30-BUS system

Bus number	Type	P_g	Q_g	P_d	Q_d	V_m	Q_{min}	Q_{max}	V_{min}	V_{max}
1	slack	0	0	0	0	1.06	0	0	0.9	1.1
2	PV	0.4	0	0.217	0.127	1.045	-0.4	0.5	0.9	1.1
3	PV	0.2	0	0	0.3	1.01	-0.1	0.4	0.9	1.1
4	PV	0	0	0.3	0	1.082	-0.06	0.24	0.9	1.1
5	PV	0	0	0.942	0.19	1.01	-0.4	0.4	0.9	1.1
6	PV	0	0	0	0	1.071	-0.06	0.24	0.9	1.1
7	PQ	0	0	0	0	1	0	0	0.9	1.1
8	PQ	0	0	0.058	0.02	1	0	0	0.9	1.1
9	PQ	0	0	0.112	0.075	1	0	0	0.9	1.1
10	PQ	0	0	0	0	1	0	0	0.9	1.1
11	PQ	0	0	0.076	0.016	1	0	0	0.9	1.1
12	PQ	0	0	0.228	0.109	1	0	0	0.9	1.1
13	PQ	0	0	0	0	1	0	0	0.9	1.1
14	PQ	0	0	0.062	0.016	1	0	0	0.9	1.1
15	PQ	0	0	0.082	0.025	1	0	0	0.9	1.1
16	PQ	0	0	0.035	0.018	1	0	0	0.9	1.1
17	PQ	0	0	0.09	0.058	1	0	0	0.9	1.1
18	PQ	0	0	0.032	0.009	1	0	0	0.9	1.1
19	PQ	0	0	0.095	0.034	1	0	0	0.9	1.1
20	PQ	0	0	0.022	0.007	1	0	0	0.9	1.1
21	PQ	0	0	0.175	0.112	1	0	0	0.9	1.1
22	PQ	0	0	0	0	1	0	0	0.9	1.1
23	PQ	0	0	0.032	0.016	1	0	0	0.9	1.1
24	PQ	0	0	0.087	0.067	1	0	0	0.9	1.1
25	PQ	0	0	0	0	1	0	0	0.9	1.1
26	PQ	0	0	0.035	0.023	1	0	0	0.9	1.1
27	PQ	0	0	0.024	0	1	0	0	0.9	1.1
28	PQ	0	0	0	0	1	0	0	0.9	1.1
29	PQ	0	0	0.024	0.009	1	0	0	0.9	1.1
30	PQ	0	0	0.106	0.019	1	0	0	0.9	1.1

P_{max} for each line is calculated assuming that the system is loaded up to 70% for the base case as given above.

B.3 Line Data

Table B.2 Line data for IEEE 30-BUS system

From Bus	To Bus	R	X	B	Tap
1	2	0.0192	0.0575	0.0264	1
1	27	0.0452	0.1852	0.0204	1
2	5	0.0472	0.1983	0.0209	1
2	11	0.057	0.1737	0.0184	1
2	13	0.0581	0.1763	0.0187	1
3	13	0.012	0.042	0.0045	1
3	28	0.0636	0.2	0.0214	1
4	7	0	0.208	0	1
5	12	0.046	0.116	0.0102	1
6	9	0	0.14	0	1
7	8	0	0.11	0	1
8	17	0.0324	0.0845	0	1
8	20	0.0936	0.209	0	1
8	21	0.0348	0.0749	0	1
8	22	0.0727	0.1499	0	1
9	14	0.1231	0.2559	0	1
9	15	0.0662	0.1304	0	1
9	16	0.0945	0.1987	0	1
10	25	0.1093	0.2087	0	1
10	29	0.2198	0.4153	0	1
10	30	0.3202	0.6027	0	1
11	13	0.0119	0.0414	0.0045	1
11	27	0.0132	0.0379	0.0042	1
12	13	0.0267	0.082	0.0085	1
13	28	0.0169	0.0599	0.0065	1
14	15	0.221	0.1997	0	1
15	18	0.107	0.2185	0	1
15	23	0.1	0.202	0	1
16	17	0.0824	0.1932	0	1
18	19	0.0639	0.1292	0	1
19	20	0.034	0.068	0	1
21	22	0.0116	0.0236	0	1
22	24	0.115	0.179	0	1
23	24	0.132	0.27	0	1
24	25	0.1885	0.3292	0	1
25	26	0.2544	0.38	0	1
29	30	0.2399	0.4533	0	1
13	7	0	0.208	0	0.978
13	8	0	0.556	0	0.969
11	9	0	0.256	0	0.962
28	10	0	0.396	0	0.968

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