Analysis of Security Constrained Optimal Power Flow with Thyristor Controlled Series Compensator

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Submitted By

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Declaration

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

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

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Abstract

The Optimal Power Flow (OPF) is very popular in power system analysis and it carried out to obtain the optimal settings of control parameters. Further, the security of the optimal schedule shall be investigated under network contingencies. In this dissertation, the Security Constrained Optimal Power Flow (SCOPF) is formulated to analyze the performance during healthy conditions and in contingency, which involves loss of a network segment such as transformer or transmission line etc. The formulation is extended to include the effect of Thyristor Controlled Series Compensator (TCSC). The performance has been analyzed for base case and the contingency case of single line outage. The OPF is solved by Newton's method and the Particle Swarm Optimization (PSO).The base case is solved by both the methods. The contingency state solution under TCSC is solved by PSO. Due to the inclusion of TCSC in the system, line flows are brought within limits and system's security is restored. The analysis is carried out on standard IEEE test systems and the results are compared.

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List of Symbols

a_i, b_i, c_i	Fuel cost coefficients of generator i
β	Scalar step length
c	Contingency state
C_1, C_2	Acceleration constants
δ_i	Voltage angle at bus i
g	Gradient of augmented function
H	Hessian of augmented function
IT	Current iteration
IT^{MAX}	Maximum number of iterations
L_0	Set of overloaded lines
λ_{pi}	Lagrangian multiplier for active power balance at bus i
L_p	Penalty for line flow limit violation
λ_{qi}	Lagrangian multiplier for reactive power balance at bus i
m	Integer exponent
NB	Number of buses
NG	Number of generators
NL	Number of lines
NP	Number of particles in swarm
NV	Number of PV buses
P_i	Real power injection at bus i
P_{ij}^r	Position of member j of particle i at iteration r
P_{di}	Real power load connected to bus i
P_{gi}	Real power output of generator connected to bus i
P_p	Penalty for active power generation limit violation
Q_i	Reactive power injection at bus i
Q_{di}	Reactive power load connected to bus i
Q_{gi}	Reactive power output of generator connected to bus i
Q_p	Penalty for reactive power generation limit violation
r_c	Degree of compensation
R	Pointer pointing generations
R_1, R_2	Random numbers between [0,1]
S	Direction of search
S_l	MVA flow in line l
S_l^{max}	MVA rating of line l

u	Set of controllable variables
v_{ij}^{r}	Velocity of member j of particle i at iteration r, $V_j^{min} \leq v_{ij}^{r} \leq V_j^{max}$
V_i	Voltage magnitude at bus i
V_p	Penalty for load bus voltage limit violation
w	Inertia weight factor
w^{max}	Final inertial weight, taken as 0.9
w^{min}	Initial inertial weight, taken as 0.2
x	Set of dependent variables
X	Vector consisting of $(P_g, \delta, \lambda_p, \lambda_q, \|V\|)$

List of Abbreviations

CSI	Contingency Sensitivity Index
c-SCOPF	Corrective SCOPF
FACTS	Flexible Security Constrained Optimal Power Flow
OPF	Optimal Power Flow
pr-SCOPF	Preventive SCOPF
PSO	Particle Swarm Optimisation
SCOPF	Security Constrained Optimal Power Flow
SI	Severity Index
SO	System Operator
TCSC	Thyristor Controlled Series Compensator

Chapter 1

Introduction

1.1 Overview

Optimal Power Flow (OPF) is being implemented in the power system studies since 1960's. One of the major drawbacks of OPF is that it optimizes a single configuration of the system at a time. The System Operator (SO) also needs to know system robustness for different contingencies and the operational constraints for various contingencies. This requires the development of an extension to OPF problem which takes into consideration pre and post-contingency constraints altogether.

The Security Constrained Optimal Power Flow (SCOPF) is a non-linear, static optimization problem with discrete and continuous variables [1]. It aims at optimization of an objective along with the satisfaction of system's equality and inequality constraints. These constraints are valid for both base and contingency state.

From the history of fifty years, it is concluded that OPF is one of the powerful and is extensively used to solve non-linear optimization problems. Generally, it optimizes the power generation, transmission, and distribution network operation while satisfying operating and control limits. A variety of its formulations and techniques for the optimal solution has been used in history and still there are new techniques getting emerged. This emergence is due to recent electricity markets and integration of traditional plants with the renewable energy sources. Nearly all the mathematical approaches can be applied to solve OPF problem and from many decades, the developers are trying to develop software being able to solve OPF efficiently. The OPF solution can be broadly categorized as a conventional and an intelligent method. Conventional techniques involve Newton's method, Gradient method, Quadratic programming, Linear programming and Interior point method. Intelligent techniques include Artificial Neural Networks (ANNs), Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Fuzzy systems, etc. The accuracy and superiority of the solution depend wholly on the chosen methodology or technique.

The classical methods are mainly mathematically formulated and require to be simplified for obtaining the solution. Handling qualitative constraints become a typical task in these methods. Moreover, their poor convergence characteristics and being able to find a single solution in a single run makes them practically infeasible and expensive for large power systems. To overcome these shortcomings, recent past developed many intelligent techniques. Being versatile in handling various constraints and having the ability to find many optimal solutions in a single run makes them perfectly suitable for multi-objective optimization problems. Further, their fast convergence and excellence non-linear modeling make them applicable to large power systems.

The gradient method can be fitted to highly constrained optimization problems but penalties and inequality constraints deteriorate the sparsity of the matrix and increase complication in obtaining a solution. Newton's method, on the other hand, is fast, robust and can handle inequality constraints well but very sensitive to initial conditions. Linear programming is effective for local and contingency constraints but lacks in accuracy due to its approximations. For ill-conditioned and divergent systems, Quadratic programming is best suited but large dimensioned problems are hard to handle. One of the most efficient algorithms is Interior point method with great accuracy and speed. But it has a drawback that it is based on continuity and differentiability which is a practical impossibility. All these methods have a common drawback that they can't be applied on discrete variables like transformer tappings.

GA is one of the intelligent techniques, which can provide global optimum solutions without getting trapped in local minima. But as the length of chromosome increases, the quality of obtained solution weakens. One of the modern approaches is PSO for large and non-convex optimization problems. It is easy in implementation, simple in concept, and fast in convergence. It is flexible enough to provide a balance between local and global exploration and exploitation of the search area.

These methods can be equally applied to the OPF as well as SCOPF problem. Regarding the security of system, a system operates in a particular operating state at a time [2]. These states are described by state transition diagram shown in Fig. 1.1. Most of the time i.e., 99 percent of the time system maintains its normalcy by operating in normal state. In this state, the system is fully balanced with regard to system's equality and inequality constraints. Due to the drop in generation, security of the system is reduced and system enters the alert state. But, this state fulfils all equality and inequality constraints. Preventive control measures can help restoration of the normalcy of the system. If somehow these rescue actions fails, system enters the emergency operating state. Some or all the inequality constraints get violated in this state but equality constraints remain intact. This state can also be reached directly from normal state if system faces a considerable disturbance. This state is characterised by implementation of emergency control actions to return to normal form. Further, if these actions fail system enters extremis state leading to system islanding and violating both equality and inequality constraints. Overloading of equipment may also lead to system blackout. After this system starts restoring itself by going through the restorative state taking hours or few days.

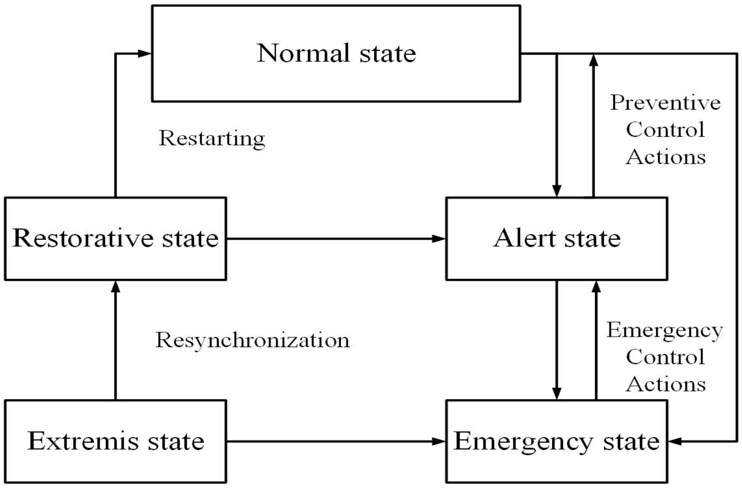

Figure 1.1: State transition diagram

1.2 FACTS in Power System

FACTS are static devices based on power electronics technology which are capable enough to improve the power handling capacity of the line or provide additional control on network [3].

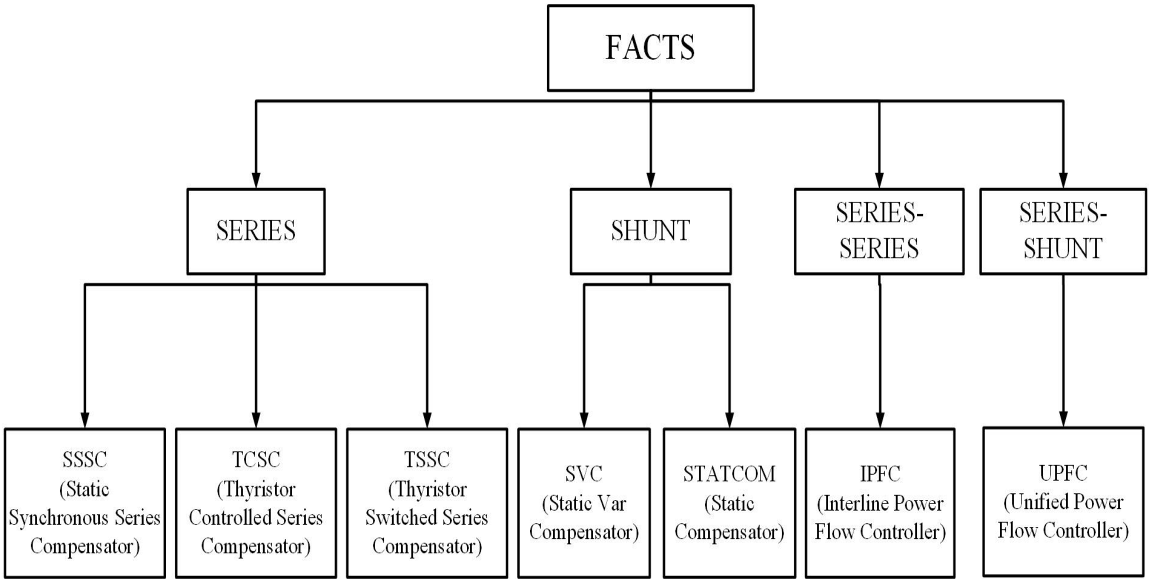

Figure 1.2: FACTS devices

FACTS devices have the ability to control nodal voltage magnitudes and angles, impedance of line, active and reactive power. These can be series or shunt devices as shown in Fig. 1.2. Series FACTS devices are mainly used to control power flow across the network. Shunt devices improve the voltage profile of the system. Series-series device like IPFC provides dynamic compensation and is effective in controlling flows across the lines. Similarly, series-shunt device like UPFC is most commonly used to improve the stability of system. One of the most common series FACTS device is TCSC. It allows smooth and continuous control of impedance of line and provides fast response. But, due to their high cost they are placed only on most severe lines.

1.3 Literature Review

OPF has been extensively used from ages to decide the optimal generation schedule such that total operating cost may get reduced. From decades, many books are written on OPF and its solution techniques. Wood and Wollenberg [4], presented in detail the conventional methods for the solution of Optimal Power Flow (OPF). The merits and demerits of all methods are analysed in proper sequence. Similarly, Chakrabarti and Halder [5], discussed in detail classical methods for solving OPF. It also discussed power system stability and control and modelling of system components. Again, Jizhong [6], covered all the conventional optimization techniques for solving OPF defining the superiority of one method over the other. Kothari and Dhillon [7], numerically supported the superiority of evolutionary based methods over classical techniques for OPF and SCOPF solution.

There are many classical methods on OPF including Gradient's method, Newton's method, Linear and Non-linear programming, and Quadratic programming etc. Rasheed and Kelly [8], presented the solution of OPF using the Newton's method or Hessian matrix method. The overall problem formulation includes the addition of equality constraints using Lagrangian multipliers. It is seen that convergence characteristics and storage is better than other classical methods. Again, Santos and Costa [9] proposed OPF solution using Newton's method applied to the augmented Lagrangian function. All equality and inequality constraints are aggregated in this function. The Hessian matrix being sparse in nature increases the speed of computation. Costa and Costa [10], described improved Newton's method approach for solving OPF problem. The linearized system helps in the calculation of Lagrangian multipliers directly.

Recent research showed the overshadowing of evolutionary based techniques for solving complex non-linear problems. Abido *et al.* [11], proposed an evolutionary based Differential Evolution (DE) algorithm for obtaining OPF solution. The algorithm has been successfully used for voltage stability improvement, voltage profile enhancement, and fuel cost minimization. Another evolutionary technique is Particle Swarm Optimization (PSO). Abido [12], deals with PSO technique to obtain optimal settings of control variables for OPF solution. PSO is considered as an optimization technique free of derivatives and assumptions for optimized objective functions. The disadvantages of insecure convergence and complex algorithms are completely eliminated in this technique.

Further improvement in system performance is seen when system is equipped with power electronics based static equipments called FACTS devices. System controllability and operating flexibility is enhanced after their installation. Hingorani and Gyugi [3], gave a detail description and modelling of all types of FACTS devices. Their applications in power system for stability and control is discussed along with each FACTS device. Enrique *et al.* [13], gave a detail description of various classical optimization techniques and their applications. Further, modelling of various FACTS devices in these techniques is also suitably described.

One of the device in FACTS family is Thyristor Controlled Series Compensator (TCSC). It is installed in series with the line and modifies the reactance of the line. Many models of TCSC are proposed and one of them is TCSC firing angle model. Ambriz-pe [14], discussed TCSC firing angle model for solving OPF problem using classical Newton's method approach. TCSC firing angle is considered as a new state variable in OPF algorithm. Another FACTS device is Static Var Compensator (SVC). Rao *et al.* [15], proposed Newton's algorithm approach for reduction of operating cost using SVC model. Further, all the security-related constraints are satisfied during the implementation of the algorithm. Alabduljabbar and Milanovi [16], researched on the reduction of cost of generation by introducing FACTS devices into the power network. FACTS devices are placed in the network in accordance with a new algorithm called Low Discrepancy Sequences (LDS), such that cost of active and reactive power generation can be minimized. Rao and Vaisakh [17], solved OPF with multiple objectives using Adaptive Clonal Selection Algorithm (ACSA) with multi-type FACTS devices in the network. Clonal Selection is an evolutionary procedure which does the cloning of antibodies for hyper maturation. The cost of generation, voltage stability, and transmission loss are the multiple objectives of the paper. Prasad and Mukherjee [18], proposed Symbiotic Organism Search (SOS) which is an inspiration from organism's interactions in an ecosystem. OPF problem consisting of FACTS is solved with the help of SOS algorithm.

Bhattacharya and Gupta [19], implemented fuzzy logic based GA and DE for obtaining optimal schedule and settings of the power network. TCSC and SVC are successfully employed for lowering congestion and optimizing the power system operation. Qing [20], compared three different methods for the solution of probabilistic OPF (P-OPF). The three methods include Quasi Monte Carlo Simulation (QMCS), Point Estimate Method (PEM) and Latin Hypercube Sampling (LHS). Khan *et al.* [21], presented operation of FACTS devices for enhancing power system security. Through the control of the active power of series FACTS devices, line overloads are controlled. Similarly, by the control of the reactive power of shunt FACTS devices, low voltage problem is solved. Thus, UPFC can solve both the problems simultaneously, being a combination of series and shunt device. Acharjee [22], presented the application of Evolutionary Algorithm in restructured power systems. Self-Adaptive Differential Evolutionary (SADE) algorithm is used for OPF solution including Unified Power Flow Controller (UPFC). With the help of UPFC line losses are reduced and power flow in lines is also enhanced. Sookananta [23], presented Differential Evolution (DE) algorithm for placing FACTS devices. Its performance is then compared with other techniques like Sensitivity Index and Genetic Algorithm.

Idris *et al.* [24], implemented Bees algorithm for placement of FACTS device. A multi-objective problem is formed which includes enhancing Available Transfer Capability (ATC), reduction of overall cost- generation cost and instalment cost. Non-Dominated Sorting GA is used for validating the results. [25], worked on finding best location of FACTS devices through the help of GA such that voltage stability can be improved and reactive losses of the system can be minimized. Steady state analysis of various FACTS devices is done and for this, their static models are taken into consideration. Singh *et al.* [26], carried a research on PSO with Ageing Leaders and Challengers (ALC-PSO) for the solution of OPF. ALC-PSO is inspired from the natural law that every organism present on this earth gets old and has a limited lifetime. The leader becomes old with time and new leaders emerge with time to accomplish particular tasks. If the old leader of the swarm is capable enough to direct the swarm to better positions then it lives otherwise, the new enthusiastic leader comes into action. Chao and Yann [27], conducted a study on hybrid optimization method for OPF using FACTS devices. Hybrid optimization technique combines harmony search and ant system algorithm. The study gives optimal location and values of FACTS devices for placement in transmission lines.

System security is considered as a challenging issue to power system developers and engineers. When Optimal Power Flow is run along with network security constraints then the term Security Constrained OPF (SCOPF) comes in existence. This security action is implemented by incorporating FACTS devices into the system. Many researchers worked on SCOPF problem using Conventional and non-Conventional methods and FACTS device placement. Capitanescu *et al.* [28], deals with SCOPF problem and its applications in the power system. IPM (Interior Point Method) is proposed a methodology for the solution of SCOPF problem. The three applications considered here are the minimization of fuel cost, maximum power transfer and minimizing congestion. Floran [29], carried a research on enhanced Risk-Based AC SCOPF (RB-SCOPF) technique which helps System Operators (SO) security and economy in the trade-off. This technique involves short-term thermal post-contingency limits which avoid cascade tripping of line. Nima and Hossein [30], implemented novel Robust Differential Evolution Algorithm (RDEA) for SCOPF using detailed generator model.

Souza *et al.* [31], studied various cases in power system through Sensitivity Analysis (SA) done by OPF. System's operating points are found out for the base case and the case involving perturbations in the system. In this case, SA is used to evaluate the operating points. Fiacco's theorem is the basis of SA in the paper. Duong *et al.* [32], carried a research on secured OPF under normal and contingency state through optimal placement of TCSC. Optimal location of TCSC is determined by min cut algorithm and then OPF is solved with TCSC in the network for both normal and contingency state. Kamel *et al.* [33], carried Sensitivity Analysis and ranking procedure for optimal location of TCSC. Further, Non-dominated Sorting GA (NSGA) technique has been successfully used to obtain optimal setting of TCSC. By placing TCSC reactive power losses and generation cost of the system are reduced effectively. [34], discussed enhanced SCOPF using FACTS devices. Polprasert *et al.* [35] implemented Time-Varying Acceleration Coefficients (TVAC-PSO) for the solution os SCOPF problem. This PSO has a self-organizing hierarchical structure with TVAC. Generator opearting and security constraints of the network are satisfied such that fuel cost is minimized in base case and line overloads are minimized during any contingency in the network. Raju and Madhavi [36], proposed PSO technique for optimal setting of TCSC. An Outage of a single line is considered in the paper. Reactance model of TCSC is considered for congested line power flow control. Contingency Sensitivity Index (CSI) decides the location of TCSC and PSO decides the value of TCSC to be placed on the overloaded line. James and Santiago [37], proposed an extension to traditional SCOPF as Flexible SCOPF (FSCOPF). In this methodology, FACTS based power routers are used in the post-contingency state.

1.4 Objective of the Work

The objective of this dissertation work is to solve OPF with two different techniques. One of them is classical Newton's method and the other is an intelligent technique called Particle Swarm Optimization (PSO). Further, the contingency case or Security Constrained OPF problem is solved by PSO. With this algorithm, SCOPF problem is efficiently solved to obtain new settings of power system after a line outage. This technique explores the search space efficiently and effectively by creating a balance between exploring and exploiting of the search space.

1.5 Dissertation Organization

The dissertation entitled “Analysis of Security Constrained Optimal Power Flow with Thyristor Controlled Series Compensator” has been summarized in five chapters. Chapter 1 gives a brief overview to the dissertation, literature review and the objective of the research work. Chapter 2 gives a detail description of Optimal Power Flow (OPF) and Newton’s method approach for OPF. Chapter 3 presents in detail Security Constrained OPF and PSO implementation for SCOPF solution. It also describes TCSC modelling and its inclusion in transmission lines. Chapter 4 discusses results obtained after implementing the above mentioned techniques. IEEE 14-bus and IEEE 30-bus systems are taken as test systems and their fuel data is mentioned in Appendix A. Conclusion of the research work and future scope is given in the concluding chapter, Chapter 5 which is followed by publications, references and appendix.

Chapter 2

Optimal Power Flow

Due to the expansion and increasing competition in the existing power network, OPF is gaining much more importance such that the capability of existing transmission system can be maximized. Many of the conventional and non-conventional methods are employed to solve OPF problem. Conventional or classical methods include Gradient method, Newton's method, Linear programming, Nonlinear programming, and Quadratic programming. Similarly, Non-conventional methods include Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Differential Evolution (DE), Ant Colony Optimization (ACO), etc.

2.1 General Concept

OPF being a constrained optimization problem aims to minimize an objective function.

$$Min\ F = (x,u) \tag{2.1}$$

Subject to constraints:

$$G_j(x,u) = 0; \qquad j = 1,2,....,m \;\; (equality\ constraints) \tag{2.2}$$

$$H_j(x,u) \leq 0; \qquad j = 1,2,....,m \;\; (inequality\ constraints) \tag{2.3}$$

$$u_{min} \leq u_{max} \tag{2.4}$$

$$x_{min} \leq x_{max} \tag{2.5}$$

where u is the set of controllable variables and x is the set of dependent variables.

1. Objective: During solving SCOPF, one of the main objectives is to minimize the total operating cost of the system along with maintaining system's security. During the light load period, cheapest generators are brought into services and as the load increases, the expensive generators are brought in.

2. Control variables: The control variables are the variables which can be directly adjusted to minimize the defined objective and satisfy the constraints. These are active and reactive generation and load, voltage settings, transformer tap settings or phase shifter angle settings.

3. Dependent variables: These include those variables which are not controlled. The variables which are free or within described limits or assumed variables. Bus voltage magnitude and angles are the main dependent variables.

4. Constraints: Basically, constraints define the limits for the operation of a problem. A practical OPF problem, during some infeasibility there is a provision to relax the limits. For instance, the region which requires voltage limits relaxation may require new compensating reactive sources [38].

   (a) Equality constraints: Power flow equations define the physics of power system. It shows that the total power injection at a particular node is zero.

   (b) Inequality constraints: The equipments of power system have their limits of operation. These limits are defined for maintaining system's security and still obtaining the desired objective.

(c) Limits on Calculated Quantities: Line flows is the first limiting factor in a transmission grid. Every line in the network is assigned maximum limit in MVA which denotes the highest amount of apparent power flow through a transmission line. The thermal stress tolerance of line is also given by this constraint.

2.2 OPF using Newton's Method

Newton's method is a traditional iterative method of optimization which modifies the control variables to minimize the defined objective [7]. This objective may include the cost of generation, losses or emissions. However, among all these objectives, most common is the minimization of generation cost. During this minimization process, physical and operating limits on control and dependent variables like active and reactive power injections, transformer tap ratios, generator voltages and angles are satisfied. Load flow equations are added to the objective function by using Lagrangian multipliers. These equations are further solved to obtain the corrections which are used to reduce the value of defined objective function.

In the proposed methodology, OPF is run using Newton's method with the objective of minimization of fuel cost. For this, a constrained minimization problem is transformed to an unconstrained minimization problem by addition of load flow constraints to the objective using Lagrangian multiplier functions. Control variables are real power generations, voltage magnitudes at load buses, voltage angles at all buses except the slack bus. Active and reactive power balance equations are included in the objective function using Lagrangian multipliers.

2.2.1 Algorithm of Newton's Method

1. Read system data: Fuel data, line data, and bus data for the considered power system network.

2. Y_{BUS} calculation: Calculate Y_{BUS} of the system using the algorithm for Y_{BUS}.

3. Initialization: Calculate the initial values of λ_p using the formula given below [5].

$$\lambda_p = \frac{(\sum_{i=1}^{NG} P_{di} + \sum_{i=1}^{NG} \frac{b_i}{2a_i})}{\sum_{i=1}^{NG} \frac{1}{2a_i}} \tag{2.6}$$

Similarly, P_g and Q_g are calculated by the formulae:

$$P_{gi} = \lambda_i - \frac{b_i}{2a_i} \tag{2.7}$$

$$Q_{gi} = P_{gi} \frac{\sum_{i=1}^{NB} Q_{di}}{\sum_{i=1}^{NB} P_{di}} \tag{2.8}$$

The initial value of λ_q is set to zero. Again, initial value of voltage is set to 1 p.u. and angle is kept at 0 for all buses except the slack bus.

4. Calculate Hessian and Jacobian matrices: To obtain the change inverse of Hessian matrix is multiplied to Jacobian matrix.

$$\begin{bmatrix} H_{P_gP_g} & 0 & H_{P_g\lambda_p} & 0 & 0 \\ 0 & H_{\delta\delta} & H_{\delta\lambda_p} & H_{\delta\lambda_q} & H_{\delta|V|} \\ H_{\lambda_pP_g} & H_{\lambda_p\delta} & 0 & 0 & H_{\lambda_p|V|} \\ 0 & H_{|V|\delta} & H_{|V|\lambda_p} & H_{|V|\lambda_q} & H_{|V||V|} \\ 0 & H_{\lambda_q\delta} & 0 & 0 & H_{\lambda_q|V|} \end{bmatrix} \begin{bmatrix} \Delta P_g \\ \Delta\delta \\ \Delta\lambda_p \\ \Delta\lambda_q \\ \Delta|V| \end{bmatrix} = \begin{bmatrix} J_{P_g} \\ J_\delta \\ J_{\lambda_p} \\ J_{\lambda_q} \\ J_{|V|} \end{bmatrix}$$

5. Check convergence: If the condition given below is satisfied then goto step number 8 otherwise goto step 6.

$$tol = [\sum_{i=1}^{NG} (\Delta P_{gi}^k)^2 + \sum_{i=2}^{NB} (\Delta\delta_i^k)^2 + \sum_{i=1}^{NB} (\Delta\lambda_{pi}^k)^2 + \sum_{i=NV+1}^{NB} (\Delta\lambda_{qi}^k)^2 + \sum_{i=NV+1}^{NB} (\Delta|V|_i^k)^2]^{1/2} \tag{2.9}$$

6. Modification of variables: The obtained change is added to the previous values of state and

control variables.

$$P_{gi} = P_{gi} + \Delta P_{gi} \tag{2.10}$$

$$\delta_i = \delta_i + \Delta\delta_i \tag{2.11}$$

$$\lambda_{pi} = \lambda_{pi} + \Delta\lambda_{pi} \tag{2.12}$$

$$V_i = V_i + \Delta V_i \tag{2.13}$$

$$\lambda_{qi} = \lambda_{qi} + \Delta\lambda_{qi} \tag{2.14}$$

7. Check limits: If any of the inequality constraint violates its limit then add a penalty for the respective limit and goto step 4 for solution updation.

8. Calculate objective: Calculate the total cost of the system.

9. Stop.

This algorithm is depicted as a flowchart in Fig. 2.1.

2.2.2 Problem Formulation with Newton's Method

The OPF problem with the classical Newton's approach is mathematically described as follows [39]:

$$Min\ F_T = \sum_{i=1}^{NG} (a_i P_{gi}^2 + b_i P_{gi} + c_i) \tag{2.15}$$

subject to

(a) Active power balance equation:

$$P_i(V,\delta) - P_{gi} + P_{di} = 0;\ (i = 1,2,...,NG) \tag{2.16}$$

(b) Reactive power balance equation:

$$Q_i(V,\delta) - Q_{gi} + Q_{di} = 0;\ (i = 1,2,...,NG) \tag{2.17}$$

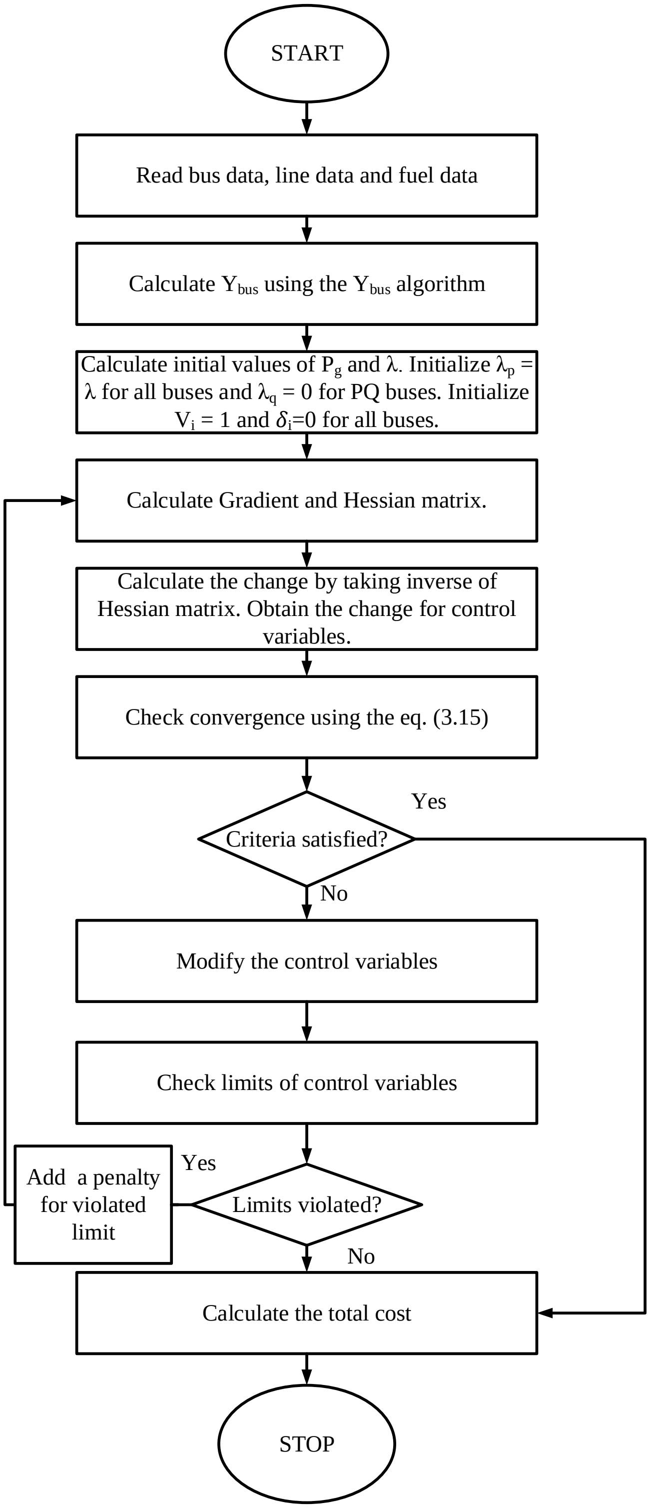

Figure 2.1: Flowchart of Newton's method

(c) Inequality constraints:

$$P_{gi}^{min} \leq P_{gi} \leq P_{gi}^{max}; \qquad (i = 1,2,...,NG) \tag{2.18}$$

$$V_i^{min} \leq V_i \leq V_i^{max}; \qquad (i = NV+1,...,NB) \tag{2.19}$$

$$\delta_i^{min} \leq \delta_i \leq \delta_i^{max}; \qquad (i = 2,3,...,NB) \tag{2.20}$$

$$Q_{gi}^{min} \leq Q_{gi} \leq Q_{gi}^{max}; \qquad (i = 1,2,...,NG) \tag{2.21}$$

$$S_l \leq S_l^{max}; \qquad (l = 1,2,...,NL) \tag{2.22}$$

where a_i, b_i, c_i determines the fuel cost coefficients of generator i, P_{gi} is the real power output of generator connected to bus i and P_{di} is the real power load connected to bus i. Similarly, Q_{gi} is the reactive power output of generator connected to bus i and Q_{di} is the reactive power load connected to bus i. P_i and Q_i gives the real and reactive power injection at bus i respectively.V_i is the voltage magnitude at bus i, δ_i is the voltage angle at bus i, NG is the number of generators, NB is the number of buses, NV is the number of PV buses, and NL is the number of lines.

When load flow constraints are included and line security constraints neglected, then the OPF problem can be formulated by constructing an augmented objective function which is given as

$$L(P_g, V, \delta) = F(P_{gi}) + \sum_{i=1}^{NB} \lambda_{pi}[P_i(V,\delta) - P_{gi} + P_{di}] + \sum_{i=NV+1}^{NB} \lambda_{qi}[Q_i(V,\delta) - Q_{gi} + Q_{di}] \tag{2.23}$$

where, λ_{pi} and λ_{qi} are the Lagrangian multipliers for active and reactive power balance at bus i.

Thus, the OPF problem represented in equations (2.15) to (2.17) is converted to unconstrained optimization problem. The unconstrained optimization problem can now be solved by Hessian matrix method or Newton's method.

The formula for search direction for Hessian matrix method is [6]

$$S^k = -[H(X^k)]^{-1} g(X^k) \tag{2.24}$$

where g determines the gradient of augmented function, H is the Hessian of augmented function, S is the direction of search, and X is the vector consisting of $(P_g, \delta, \lambda_p, \lambda_q, |V|)$.

The Hessian matrix calculated is a sparse matrix, so it can be stored using sparsity programming techniques.

The iteration calculation based on search direction is given as:

$$X^{k+1} = X^k + \beta S^k \tag{2.25}$$

where β is the scalar step length and β is calculated using quadratic interpolation.

The program terminates when convergence criteria given in equation (2.9) is satisfied.

Chapter 3

SCOPF Solution using PSO

When OPF is solved along with constraints denoting electrical security of the network then, it is termed as SCOPF [1]. It considers outage of transmission lines and other equipment. The solution obtained by running SCOPF is secure for all credible contingencies or it can be made secure by taking some corrective action, i.e., introducing FACTS devices in the system. Generator, line, transformer, compensator or apparatus failure is termed as SCOPF. Due to the recent blackouts, the importance of such system has been recognized which is able to withstand contingencies or able to work on specified limits without disturbing the whole system's operation.

SCOPF includes additional constraints for possible contingencies in power system [6]. It gives an optimal operating point for the base case such that no security violations occur even

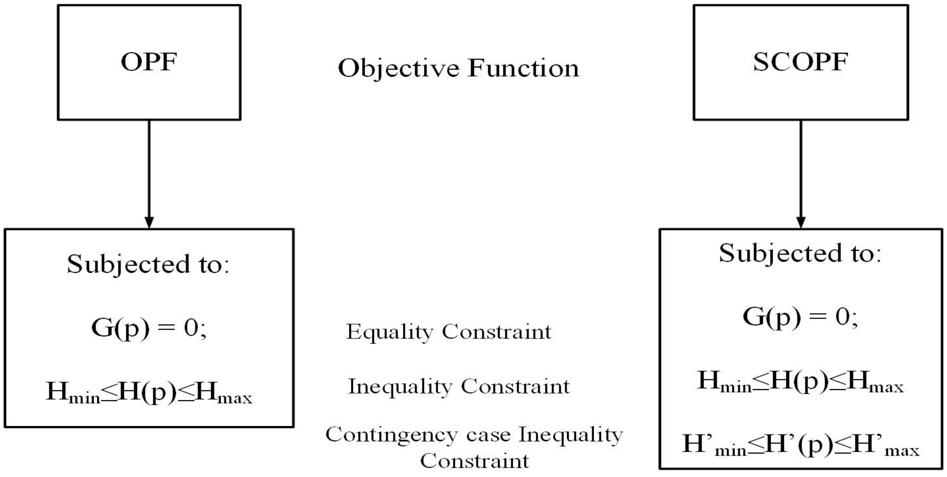

Figure 3.1: Comparision chart

when a contingency occurs. All the definitions related to OPF are valid with the inclusion of some additional security constraints which is depicted in Fig. 3.1. Contingency is considered as that configuration of the system which has emerged due to malfunctioning of any element of the system. After the occurrence of any contingency, the admittance matrix gets changed and there occurs the need to change the operating limits for different devices. Thus, equations defining the system need to be changed and new constraints need to be added. These constraints are the reflection of the previous constraints with the difference only in modified Y_{BUS} matrix. If the damaged or outaged element has no effect on admittance matrix then, upper and lower limits of damaged system element are set to zero.

The SCOPF algorithm automatically includes the new constraints into the problem. A system fault can lead to a non-feasible solution to the OPF problem. So, an algorithm may be such that it doesn't include these solutions in the final formulation.The feasibility of the solution is determined by comparison of maximum and minimum values of generators and loads in an isolated area. If demand is lower than a minimum generation or if it is higher than maximum generation then, OPF problem will yield a non-feasible solution and the respective constraints are not added to the problem.

As mentioned above OPF is a special category of SCOPF. It runs for a base case and a set of contingency states. The “N-1” criteria of contingency analysis ensure that no violation should occur after the outage of single power system element. The preventive approach of SCOPF is implemented in this case.

3.1 Types of SCOPF Problems

The main difference between the SCOPF types is allowed range for corrective actions to be taken. Accordingly, they are classified as:

1. Preventive SCOPF (pr-SCOPF)
2. Corrective SCOPF (c-SCOPF)

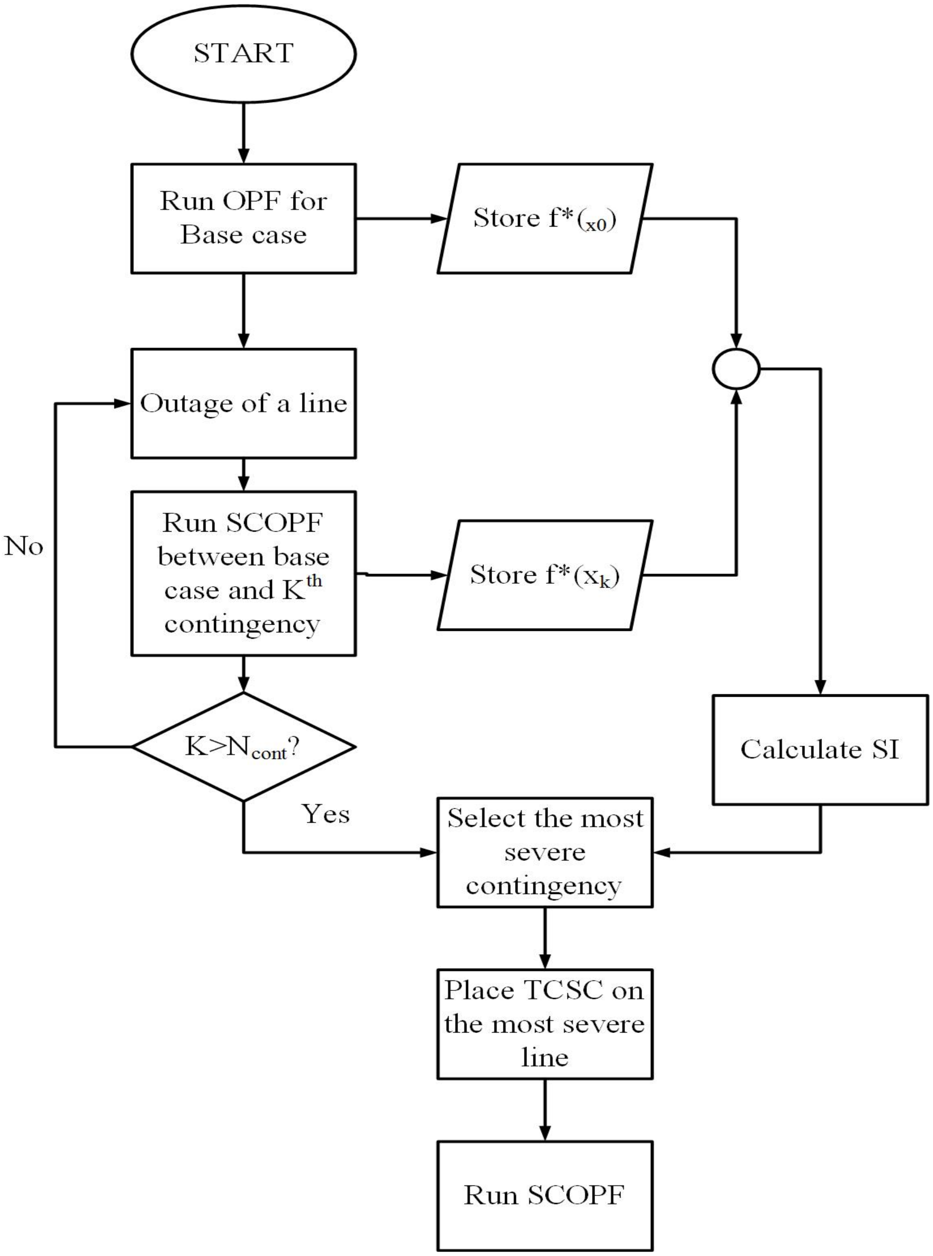

Figure 3.2: SCOPF flowchart

Preventive SCOPF

Under this SCOPF, there is no allowance for undertaking corrective actions except for those which has an automatic response to the contingency like phase shifters or tap changers. In this, it is assumed that no primary control is available.

Corrective SCOPF

In case of corrective approach, some post-contingency constraint violations can be allowed upto several minutes without damaging the equipment. For the simulation of available primary control reserves, some correction for one or some generators of the system can be done. This provides enough time for some corrective action to be implemented. In this approach, FACTS devices can be employed for corrective action as they have high response rate.
If x* is the optimum operating point then, the value of objective is higher for pr-SCOPF than c-SCOPF than OPF.

$$f(x^*_{OPF}) \leq f(x^*_{c-SCOPF}) \leq f(x^*_{pr-SCOPF}) \tag{3.1}$$

After analyzing, it became clear that many of the system contingencies don't even effect the optimal setting of the system. It is seen that only a small set of inequality constraints get activated during a contingency and effect the system's optimal settings. To reduce system's complexity, one of the approaches is "Contingency Filtering". In this SCOPF problem includes only those contingencies which are most severe. The severity is determined by the index called Severity Index (SI). This approach helps in improving the efficiency of the algorithm. The Severity Index can be found by the formula given as [39]:

$$SI = \sum_{l=1}^{L_0} (\frac{S_l}{S_{lmax}})^{2m} \tag{3.2}$$

where S_l defines the MVA flow in line l, S_l^{max} defines the MVA rating of line l, L_0 gives the set of overloaded lines, and m is an integer exponent. A flowchart of SCOPF with corrective action is depicted in Fig. 3.2.

3.2 Modelling of TCSC

TCSC is a series FACTS device. It acts as a controllable reactance that compensates the inductance of line. This leads to the reduction of transfer reactance of line in which it is connected. Basically, TCSC is a fixed capacitor in parallel with a Thyristor Controlled Reactor (TCR) for each phase as

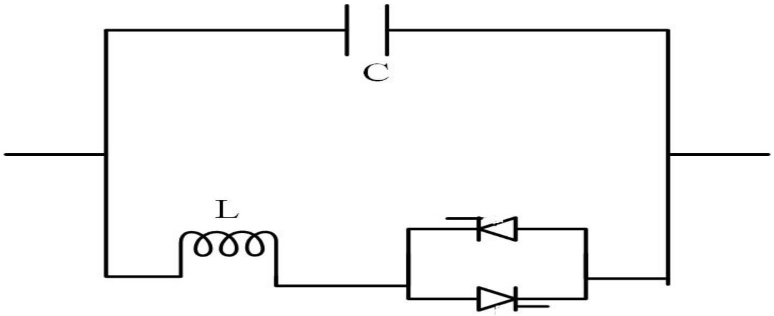

Figure 3.3: Basic module of TCSC

shown in Fig. 3.3. It is capable of operating in both inductive and capacitive regions but it is mostly used for the capacitive operation. Power system security can be enhanced by installing TCSC at critical locations in power system. It is capable of balancing the line flows in either direction. It can improve the flows of lightly loaded as well as heavily loaded lines by changing the reactance of the line in which it is connected. Heavily loaded lines divert their excess flow to the lightly loaded lines thus relieving line congestion. Due to the budgetary constraints these devices are installed in a limited number. Most severe lines are chosen for installment purpose. In steady state, TCSC acts as a static reactance. It provides continuous control of power on transmission line over a wide range [39]. Figure 3.4 shows TCSC installed in series with the line. Here, Z_{ij} is the impedance of

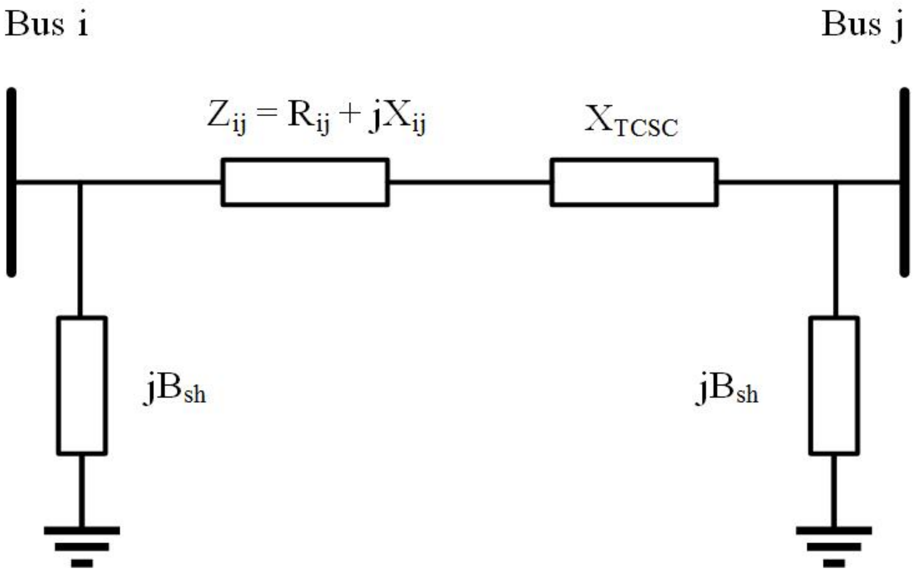

Figure 3.4: Model of TCSC

the line, X_{TCSC} is the reactance of TCSC, and B_{sh} is the susceptance of the shunt elements between bus i and j. The effective impedance of the line is the net impedance due to TCSC and the line.

3.3 Particle Swarm Optimization

One of the most reliable and efficient evolutionary based technique is PSO. Being a derivative-free algorithm, it does not impose assumptions on the defined objective. It is a motivation from social behavior of organisms like bird flocking and fish schooling. It is a well-balanced technique which can adapt to local and global exploring abilities.

PSO was first introduced by Kennedy and Eberhart in the year 1995. In this system particles fly in a multidimensional space and adjusts their positions during their flight. This is done by the knowledge of their own experience and the experience of their neighbours thus updating their positions. Let the position of the particle is given by P and its velocity by v. In a NP-dimensional space, particle j is represented as [7]:

$$P_i = [P_{i1}, P_{i2}, ..., P_{iNG}] \tag{3.3}$$

Similarly, the previous best position of the particle is given as:

$$Pb_i = [Pb_{i1}, Pb_{i2}, ..., Pb_{iNG}] \tag{3.4}$$

Among the group of particles, the index of best particles is given by:

$$G_i = [G_1, G_2, ..., G_{NG}] \tag{3.5}$$

and velocity is given as:

$$v_i = [v_{i1}, v_{i2}, ..., v_{iNP}] \tag{3.6}$$

The formula for modified velocity and position for every particle is given as:

$$v_{ij}^{r+1} = w \times v_{ij}^{r} + C_1 \times R_1 + (PB_{ij}^{r} - P_{ij}^{r}) + C_2 \times R_2 \times (G_j^{r} - P_{ij}^{r}) \tag{3.7}$$

$$P_{ij}^{r+1} = P_{ij}^{r} + v_{ij}^{r+1}; \qquad (i = 1, 2, ..., NP); (j = 1, 2, ..., NG) \tag{3.8}$$

where, NP is the number of particles in swarm, NG is the number of members in a particle, R is a pointer pointing generations, w is inertia weight factor, C_1, C_2 are the acceleration constants, R_1, R_2 are the random numbers between [0,1], v_{ij}^{r} is the velocity of member j of particle i at iteration r such that $V_j^{min} \leq v_{ij}^{r} \leq V_j^{max}$, and P_{ij}^{r} gives the position of member j of particle i at iteration r.

Here, V_j^{min} determines resolution or fitness determining the regions to be searched for current and target positions. By the past experiences it is suggested to set V_j^{max} at 10 to 20 percent of dynamic range of variable on each dimension. It being too high, particles fly over good solutions and unexplored solutions when it is too low. C_1 and C_2 are two acceleration constants giving local best and global best influence. These are mostly set to the value 2 according to the past experiences. w is termed as inertia weight which is useful in providing a balance between local and global exploration. w is found out by the following formula:

$$w = w^{max} - (w^{max} - w^{min}) / IT^{MAX} \times IT \tag{3.9}$$

Here, IT^{MAX} gives the maximum number of iterations, IT defines the current iteration, w^{min} and w^{max} determines the initial and final inertial weight, taken as 0.2 and 0.9 respectively.

3.3.1 Algorithm of PSO

1. Representing the swarm: For a system having NG generators and NP particles the swarm is represented by the following matrix:

$$\begin{bmatrix} P_{11} & P_{12} & .. & .. & P_{1NG} \\ P_{21} & P_{22} & .. & .. & P_{2NG} \\ . & . & P_{ij} & .. & . \\ . & . & .. & .. & . \\ P_{NP1} & P_{NP2} & .. & .. & P_{NPNG} \end{bmatrix}$$

2. Implementing the swarm:Random initialization of particles velocity is done through the following inequality.

$$V_j^{min} \leq V_{ij} \leq V_j^{max}; \qquad (i = 1,2,...,NP); \ (j = 1,2,...,NG) \tag{3.10}$$

3. Evaluating the objective: For satisfying the power balance equality constraint, one of the generator (generally the generator at slack bus) is taken as dependent generator. If this dependent generator violates its upper or lower limit, it is fixed at that point and a penalty is added to the objective.

4. Initializing the best position: The position having the minimum value of objective is taken as the best position of that particle.

5. Movement of particles: The new positions and velocities acquired by the swarm defines the movement of particles. This is given by eq. (3.7) and eq. (3.8).

6. Updation of new best positions: Out of all the new P_{ij}^{best}, best positions are taken as G_j^{best} and the corresponding objective is taken as f_{best}.

7. Converging criteria: There can be many criterion's for convergence and these include max. no. of iterations, specified tolerance or no. of function evaluations. Here, max. no. of iterations are taken as a criteria for stopping.

3.3.2 Problem Formulation with PSO

The problem is formulated using PSO such as to minimize total cost of production in the base case and reduction of line overloads in contingency case.

Base Case Problem Formulation

$$Min\ F_T = \sum_{i=1}^{NG} (a_i P_{gi}^2 + b_i P_{gi} + c_i) \tag{3.11}$$

subject to equality and inequality constraints given by eq. (2.16) to eq. (2.22).
The problem in base case is formulated as:

$$MinF_T + 100 * abs(P_i - P_{gi} + P_{di}) + 100 * abs(Q_i - Q_{gi} + Q_{di}) \tag{3.12}$$

If there is violation of any inequality constraint respective penalties are added to the objective function.

Contingency Case Problem Formulation

Contingency Sensitivity Index (CSI)

Due to the budgetary constarints related to installment of TCSC, they are preferred only in those lines which are most severe. To find the optimal location of TCSC, the branch which is affected most by maximum number of contingencies is found out. This is determined by an index called Contingenct Sensitivity Index (CSI). This index helps in the determination of severity of each line. It is calculated by calculating some matrices which are given below [36].

1. Participation matrix (U): This is a binary matrix with dimension of $(m \times n)$ and entries as "1"or "0". Here m is total number of single contingencies considered and n is total number of branches. $U_{ij} = 1$, if branch j is overloaded for a contingency at branch i else $U_{ij} = 0$.

2. Ratio matrix (W): This is also an $(m \times n)$ matrix. It determines the excess power flow w.r.t. maximum power that can flow through the line.

$$W_{ij} = \frac{P_{ij,cont}}{P_{ij,max}} - 1 \tag{3.13}$$

3. Contingency Probability Array (P): It is of dimension $m \times 1$ and gives probability of branch

outage. It is given as:

$$P_{m\times 1} = [p_1, p_2, ..., p_m]^T \tag{3.14}$$

The probability of occurence of a contingency is given by p_i is which is taken as 0.02.

Contingency Sensitivity Index (CSI): It is taken as summation of all sensitivities due of branch j for single line outage. It is given as:

$$CSI_j = \sum_{i=1}^{m} (p_i u_{ij} w_{ij}) \tag{3.15}$$

Here, p_i, u_{ij}, and w_{ij} are the elements of P, U, and W respectively.

According to the calculated CSI, branches are ranked most severe to the least severe. Large value of CSI means most severe line. When it is required that more than one TCSC is to be installed then, lines are chosen from highest to lowest CSI rank.

The objective in contingency state is maintaining line flows within limits or minimize the value of CSI.

$$Min\ CSI = \sum_{i=1}^{m} (p_i u_{ij} w_{ij}) \tag{3.16}$$

subject to
active and reactive power balance equation during contingency:

$$P_i^c(V,\delta) - P_{gi}^c + P_{di}^c = 0;\ (i = 1,2,...,NG) \tag{3.17}$$

$$Q_i^c(V,\delta) - Q_{gi}^c + Q_{di}^c = 0;\ (i = 1,2,...,NG) \tag{3.18}$$

and
contingency case line flow and TCSC reactance constraints

$$S_l^c \leq S_l^{cmax};\ (l = 1,2,...,NL) \tag{3.19}$$

$$X_{ci}^{min} \leq X_{ci} \leq X_{ci}^{max};\ (i = 1,2,...,NTCSC) \tag{3.20}$$

where c is the c^{th} contingency state.

The range of TCSC is mostly taken between $-0.5X_{line}$ and $0.5X_{line}$ to avoid over compensation.

Overall Problem Formulation

The objective of SCOPF is minimizing fuel cost in base case and minimizing overloads in contingency case while satisfying equality and inequality constraints for both cases. Equality constraints are fulfilled at each node by satisfying the active and reactive power balance equation at each bus and their difference is taken as a penalty which is added to the objective. Similarly, on the violation of inequality constraints penalties are added to the objective function and the problem is thus formulated as [39]:

$$Min\ f = F_T + (w \times CSI_l) + \sum_{i=1}^{NG} P_{pi} + \sum_{i=1}^{NG} Q_{pi} + \sum_{j=NV+1}^{NB} V_{pj} + \sum_{i=1}^{Nl} L_{pi} \tag{3.21}$$

where P_p and Q_p determines the penalty for active power generation limit violation, V_p is the penalty for load bus voltage limit violation, and L_p is the penalty for line flow limit violation. These are defined as [39]:

$$P_p = \begin{cases} K_p(P_g - P_{gmax}); & if\ P_g \geq P_{gmax} \\ K_p(P_{gmin} - P_g); & if\ P_g \leq P_{gmin} \\ 0; & otherwise \end{cases} \tag{3.22}$$

$$Q_p = \begin{cases} K_q(Q_g - Q_{gmax}); & if\ Q_g \geq Q_{gmax} \\ K_q(Q_{gmin} - Q_g); & if\ Q_g \leq Q_{gmin} \\ 0; & otherwise \end{cases} \tag{3.23}$$

$$V_p = \begin{cases} K_v(V_j - V_{jmax}); & if\ V_j \geq V_{jmax} \\ K_v(V_{jmin} - V_j); & if\ V_j \leq V_{jmin} \\ 0; & otherwise \end{cases} \tag{3.24}$$

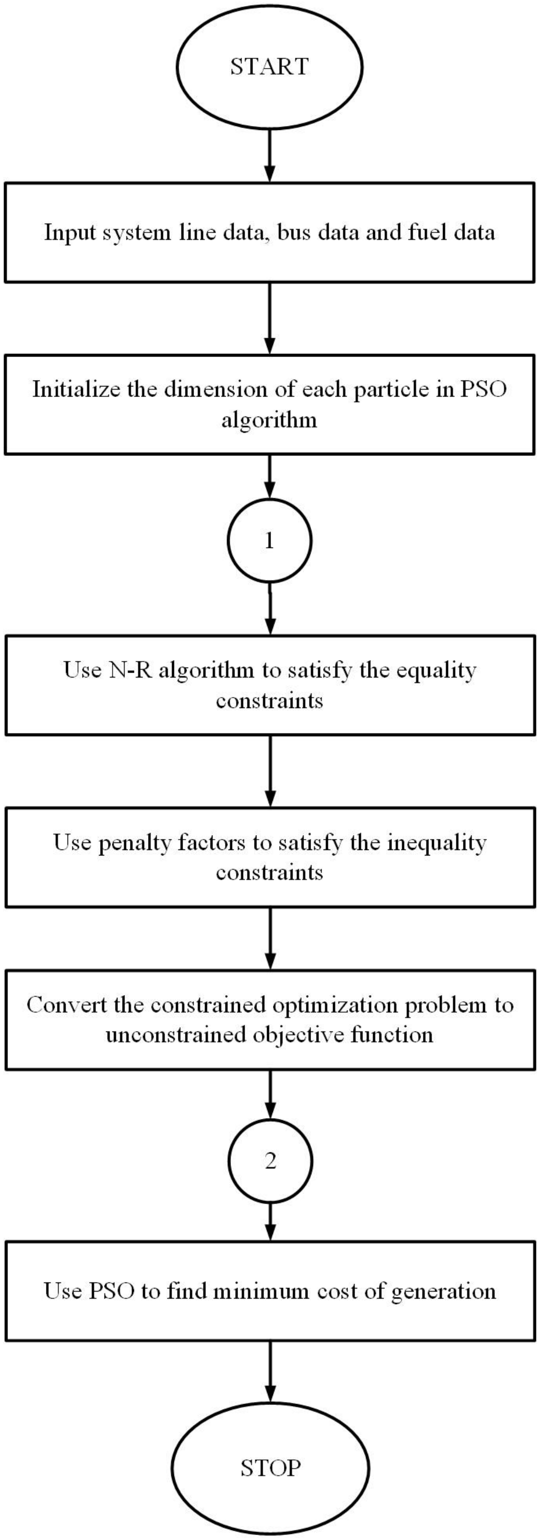

Figure 3.5: Flow diagram for OPF using PSO

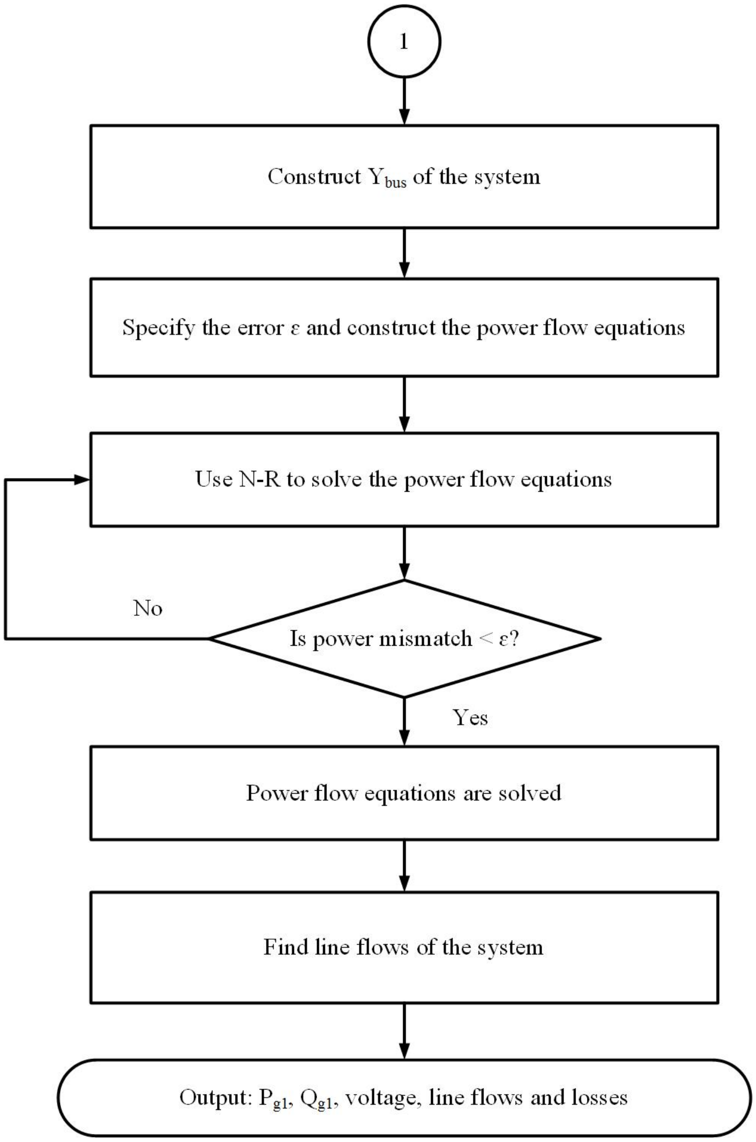

Figure 3.6: Flow diagram for Load Flows

$$L_p = \begin{cases} K_l(S_l - S_{lmax}); & if\ S_l \geq S_{lmax} \\ 0; & otherwise \end{cases} \tag{3.25}$$

The degree of penalty is controlled by penalty factor. It is usually a real positive number. Higher value of penalty factor can lead to poor convergence. So, optimization process is started with low value of penalty and is increased when limit violates above a specified limit. These penalties are added to the objective function. A flowchart depicting SCOPF using PSO is given in Fig. 3.5, Fig. 3.6, and Fig. 3.7.

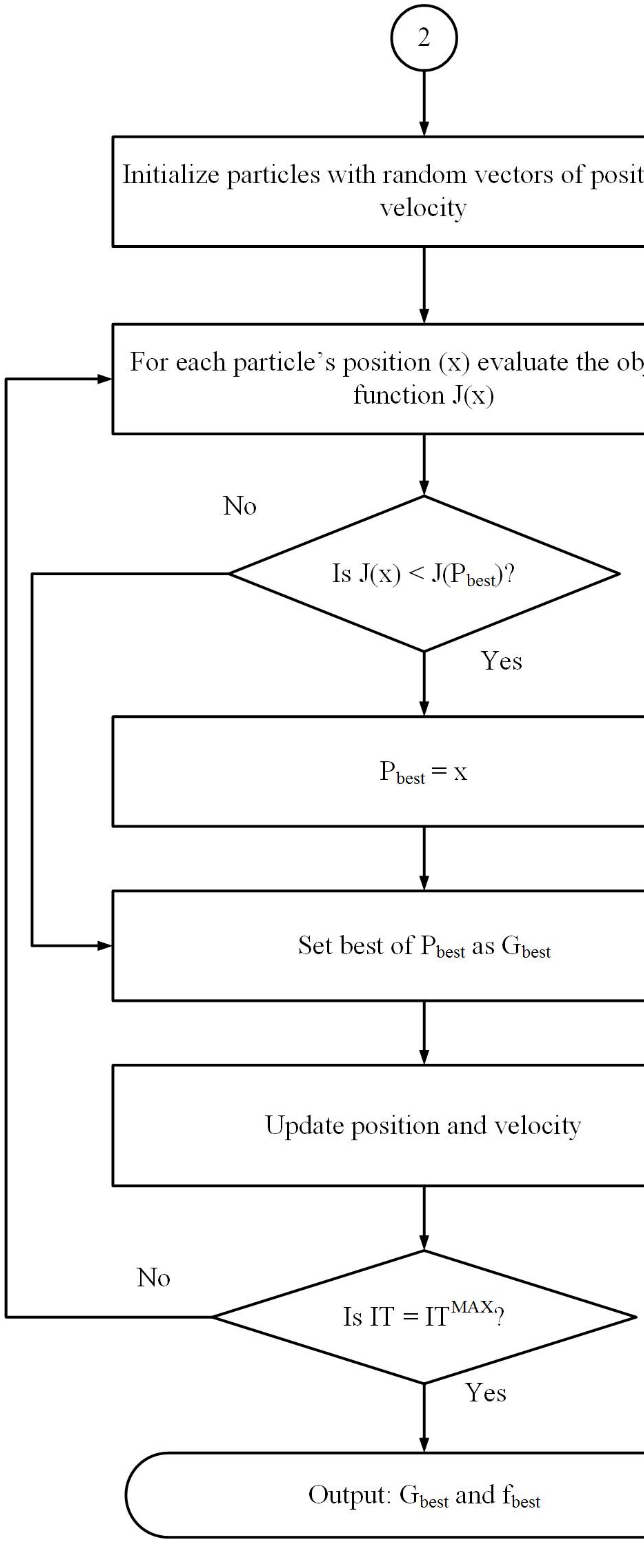

Figure 3.7: Flow diagram for PSO

3.3.3 Inclusion of TCSC in PSO

A TCSC is a series FACTS device which is capable of operating in inductive as well as capacitive region. Here TCSC provides a capacitive operation. In steady state, TCSC acts as a static reactance. The active and reactive power is injected by TCSC at nodes *i* and *j* to which it is connected as shown in Fig. 3.8. This has the advantage that the symmetry of admittance matrix remains the same. The active and reactive power injected by TCSC is given as [40]:

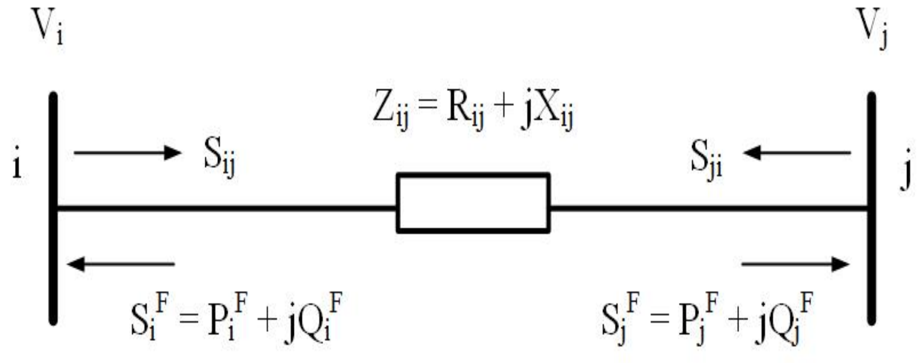

Figure 3.8: Power Injection by TCSC

$$P_i^F = V_i^2 \Delta G_{ij} - V_i V_j (\Delta G_{ij} cos(\delta_i - \delta_j) + \Delta B_{ij} sin(\delta_i - \delta_j)) \tag{3.26}$$

$$Q_i^F = -V_i^2 \Delta B_{ij} - V_i V_j (\Delta G_{ij} sin(\delta_i - \delta_j) - \Delta B_{ij} cos(\delta_i - \delta_j)) \tag{3.27}$$

$$P_j^F = V_i^2 \Delta G_{ij} - V_i V_j (\Delta G_{ij} cos(\delta_i - \delta_j) - \Delta B_{ij} sin(\delta_i - \delta_j)) \tag{3.28}$$

$$Q_j^F = -V_i^2 \Delta B_{ij} + V_i V_j (\Delta G_{ij} sin(\delta_i - \delta_j) + \Delta B_{ij} cos(\delta_i - \delta_j)) \tag{3.29}$$

$$\Delta G_{ij} = \frac{x_c r_{ij} (x_c - 2x_{ij})}{(r_{ij}^2 + x_{ij}^2)(r_{ij}^2 + (x_{ij} - x_c)^2)} \tag{3.30}$$

$$\Delta B_{ij} = \frac{-x_c(r_{ij}^2 - x_{ij}^2 + x_c x_{ij})}{(r_{ij}^2 + x_{ij}^2)(r_{ij}^2 + (x_{ij} - x_c)^2)} \tag{3.31}$$

where $x_c = r_c \times x_{line}$ and r_c is the degree of compensation.

After installing TCSC, power balance equations at nodes i and j are modified as

$$P_i(V,\delta) - P_{gi} + P_{di} + P_i^F = 0 \tag{3.32}$$

$$Q_i(V,\delta) - Q_{gi} + Q_{di} + Q_i^F = 0 \tag{3.33}$$

$$P_j(V,\delta) - P_{gj} + P_{dj} + P_j^F = 0 \tag{3.34}$$

$$Q_j(V,\delta) - Q_{gj} + Q_{dj} + Q_j^F = 0 \tag{3.35}$$

Chapter 4

Results and Discussions

OPF is solved with the help of Newton's method and PSO methodology was applied to SCOPF problem for IEEE 14-bus and IEEE 30-bus systems. To determine the results, two cases are considered. In case 1 or base case, OPF is solved with active and reactive power balance constraints at each bus and real power generation, voltage magnitude and voltage angles taken as control variables. Whereas in case 2 or contingency case, SCOPF is solved with line flows taken within limits while including all base case control variables. V_{min} and V_{max} are taken to be 0.9 and 1.06 respectively.

The test systems considered here are IEEE 14-bus and IEEE 30-bus system. Data related to these test system has been defined in Appendix A.

4.1 Test System 1: IEEE 14-bus System

This system is equipped with 5 generators, 20 lines, and 14 buses. Considering bus 1 as slack bus, generator at bus 1 is taken as dependent generator in PSO scheme. Therefore, in base case number of particles in the swarm are 4.

4.1.1 Base Case Results

No contingency is considered here and Newton's method and PSO are used to solve OPF to find optimal schedule of the power system. The generator cost coefficients are given in Appendix

A. Objective here is minimization of fuel cost. Table 4.1 gives the generation schedule obatined through two different techniques, namely-Newton's method and PSO. It is seen that there is a significant reduction of fuel cost when PSO is used as an optimization technique.

Table 4.2 shows the line flows in base case or when system is in a healthy state. It is seen that line flows are within their maximum specified limits for both the applied techniques.

Table 4.1: Base Case Generation

Method	G_1	G_2	G_5	G_8	G_{11}	Fuel cost
PSO	191.2769	36.2133	21.5729	10.0000	10.0000	8121.5($\$/hr$)
Newton's Method	183.5056	49.8812	22.9032	4.7172	10.4053	8253.8($\$/hr$)

Table 4.2: Base Case Flows

S.No.	From Bus	To Bus	Line Flows (MVA)(PSO)	Line Flows (MVA)(Newton's method)	Max. MVA Flow
1	1	2	130.3657	110.55	135
2	1	5	63.7083	15.91	65
3	2	3	59.3843	39.29	65
4	2	4	49.2377	13.10	65
5	2	5	38.6031	17.42	50
6	3	4	19.5356	16.45	65
7	4	5	54.4505	52.46	65
8	4	7	20.6484	37.50	55
9	4	9	14.0893	11.95	32
10	5	6	33.9529	18.74	45
11	6	11	7.8783	2.76	18
12	6	12	8.2885	1.06	32
13	6	13	20.1235	20.89	32
14	7	8	10.0004	19.35	32
15	7	9	30.6482	21.83	32
16	9	10	5.8108	2.50	32
17	9	14	10.7267	10.57	18
18	10	11	3.8858	2.52	12
19	12	13	1.9732	0.40	12
20	13	14	5.9014	1.81	12

4.1.2 Contingency Case Results

In this case 6 contingencies are considered at 6 different lines. Single line outage is considered as a contingency in the system. Losing a line can affect or disturb the flows in the adjacent lines of the system. Thus, CSI is an index which determines the amount of disturbance encountered by a line due to a change in system's configuration. Thus, every line is ranked according to the severity it encounters. Table 4.3 shows the summary of the contingencies and their effects on other lines. The lines for placing TCSC are identified by the CSI of line.

Table 4.3: Contingency Case Line Flows

Outaged Line	Overloaded Lines	Line Flows (MVA)	Max. Limit (MVA)	CSI	Line Ranking
1	2	209.8944	135	2.1746	1
	7	120.0678	65	1.0136	2
2	1	197.6603	135	0.0919	1
	3	69.7112	65	0.0269	4
	4	69.9827	65	0.0269	3
	5	65.3347	50	0.0583	2
4	2	77.1662	65	0.0397	2
	3	73.0861	65	0.0320	4
	5	57.2999	50	0.0345	3
	7	87.4049	65	0.2847	1
5	2	76.4972	65	0.0384	2
	3	66.4880	65	0.0219	1
13	15	33.6507	32	0.0245	3
	17	19.5538	18	0.0279	2
	19	17.2937	12	0.0863	1
17	20	16.8805	12	0.0783	1

Setting of TCSC is chosen randomly within the range $-0.5X_{line}$ and $0.5X_{line}$. In this case, due to addition of TCSC number of particles in the swarm are increased. Number of TCSC decides the size of swarm. Table 4.4 shows the lines on which TCSC are installed. After installing TCSC the OPF program is run with modified line reactance and modified cost along with CSI of line is shown in this Table. The overloading of line is reduced after installing TCSC.

4.2 Test Case 2: IEEE 30-bus System

IEEE 30-bus has 6 generators, 30 buses, and 40 lines. The generator at slack bus is taken to be a dependent generator and its generation is not obatined randomly in PSO. The size of the swarm is 5 in this case. The generator limits and cost coefficients for IEEE 30-bus is provided in Appendix A. The line and bus data for this system are taken from reference [41].

Table 4.4: TCSC placement

Outaged Line	TCSC Location	TCSC value	Fuel cost ($\$/hr$)
1	2	-0.0807	8692.0
	7	0.0124	
2	1	0.0279	7465.4
	3	-0.0063	
	4	-0.0640	
	5	0.0233	
4	2	0.0202	7843.6
	3	-0.0802	
	5	-0.0580	
	7	0.0498	
5	2	0.0182	8137.6
	3	-0.0645	
13	15	0.0998	8233.5
	19	0.0208	
17	20	0.0025	8288.7

4.2.1 Base Case Results

The optimal values of generator output and fuel cost obtained after running OPF for IEEE 30-bus system are given in Table 4.5. The results obtained by PSO are better when compared with the conventional Newton's method. Thus, PSO has proved to be superior and promising optimization technique when compared to its classical counterparts. Due to its easy implementation and derivative-free formulation, it is most commonly used in modern power system.

Similarly, Table 4.6 gives the base case line flows obtained after running two different proposed techniques. Again, line flows are found to be within their limits and system operates in a healthy operating state.

Table 4.5: Base Case Generation

Method	G_1	G_2	G_5	G_8	G_{11}	G_{13}	Fuel cost
PSO	176.7285	48.8537	21.5042	21.8470	12.1709	12.0000	803.0285($\$/hr$)
Newton's method	187.1121	49.5136	20.2672	11.6463	7.5211	7.3691	827.3118($\$/hr$)

Table 4.6: Base Case Flows

S.No.	From Bus	To Bus	Line Flows (MVA)(PSO)	Line Flows (MVA)(Newton's method)	Max. Flow (MVA)
1	1	2	118.3575	82.9695	130
2	1	3	59.2052	37.8251	130
3	2	4	35.0653	62.8382	65
4	3	4	54.8722	31.2105	130
5	2	5	63.8020	24.7346	130
6	2	6	45.3296	56.9416	65
7	4	6	47.0907	25.5401	90
8	5	7	14.8808	36.3932	70
9	6	7	34.1353	38.7928	130
10	6	8	10.7578	20.0182	32
11	6	9	22.6848	40.0626	65
12	6	10	12.6868	20.5477	32
13	9	11	23.7308	33.0532	65
14	9	10	34.5155	22.9604	65
15	4	12	36.9757	45.5063	65
16	12	13	18.3462	24.2506	65
17	12	14	8.8180	7.0474	32
18	12	15	21.2416	14.7828	32
19	12	16	10.2536	10.8510	32
20	14	15	2.4024	3.2830	16
21	16	17	6.2789	11.2134	16
22	15	18	7.3089	5.3414	16
23	18	19	4.0139	5.2443	16
24	19	20	6.3934	12.6267	32
25	10	20	8.8004	15.1963	32
26	10	17	4.9582	17.4430	32
27	10	21	18.5493	17.5191	32
28	10	22	8.8066	8.0710	32
29	21	22	2.4966	4.3052	32
30	15	23	7.6213	9.6550	16
31	22	24	6.2933	4.6632	16
32	23	24	4.1633	10.2656	16
33	24	25	1.0179	5.1466	16
34	25	26	4.2641	4.2809	16
35	25	27	5.2540	8.6864	16
36	28	27	17.5465	32.5880	65
37	27	29	6.4141	6.5552	16
38	27	30	7.2881	7.4155	16
39	29	30	3.7538	3.7946	16
40	8	28	2.4011	23.4636	32
41	6	28	15.2505	8.6472	32

4.2.2 Contingency Case Results

Different lines are opened to create a contingency in the system. The parameters of the system changes due to change in the operating point of the system. Table 4.7 shows the outage of 6 different lines of the system. Table 4.8 gives the value of TCSC which is installed at line specified by CSI. Along with this the fuel cost for modified system is given.

Table 4.7: Contingency Case Line Flows

Outaged Line	Overloaded Lines	Line Flows (MVA)	Max. Limit (MVA)	CSI	Line Ranking
1	2	192.9171	130	0.0970	1
	4	180.5376	130	0.0744	2
	7	110.3486	90	0.0452	3
2	1	182.1841	130	0.0771	1
	6	66.5554	65	0.0220	2
4	1	179.3977	130	0.0725	1
	6	65.6344	65	0.0208	2
5	6	76.9231	65	0.0392	2
	8	84.0486	70	0.0416	1
36	31	20.6525	16	0.0555	1
	33	19.6857	16	0.0458	2
7	1	133.3274	130	0.0221	2
	6	69.2904	65	0.0258	1

Table 4.8: TCSC placement

Outaged Line	TCSC Location	TCSC value	Fuel cost ($\$/hr$)
1	2	-0.0847	867.1178
	4	0.0014	
	7	0.0146	
2	1	0.0196	850.7490
	6	-0.0506	
4	1	0.0076	847.0991
	6	-0.0866	
5	6	0.0142	837.5766
	8	-0.0745	
36	31	-0.0873	843.8823
	33	0.0054	
7	1	-0.0664	847.9288
	6	0.0205	

Chapter 5

Conclusions and Future Work

5.1 Conclusions

The work on “Analysis on Security Constrained Optimal Power Flow with Thyristor Controlled Series Compensator ” has been carried out to find out optimal schedule of system for base case and in contingency. The optimal location and setting of TCSC is found during line-outage contingency to keep the line flows within their maximum defined limits. The optimal schedule of generation is found out by Newton’s method and PSO for base case, whereas the PSO is used for contingency case analysis. The optimal TCSC setting is determined with the help of contingency sensitivity index (CSI) of line by PSO. The study has been carried out on IEEE 14-bus and IEEE 30-bus test systems. The following conclusions are drawn from the work:

1. CSI technique is found to be effective in determining the severity of a line.
2. TCSC diverts the flow from heavily loaded lines to lightly loaded lines, thus relieving line congestion.
3. PSO has proved to be a very efficient technique for finding out the optimal generation as well as optimal value of TCSC.

5.2 Future Work

When a research work is being carried out, many avenues for future gets identified. The following areas can be included in future work:

1. The cost of FACTS devices can also be included in the objective function for the sake of economy.
2. Multiple contingencies can be considered and SCOPF can be incorporated to remove line overloads.
3. A multi-objective problem can be formulated such as improvement of voltage profile along with minimizing overloads. UPFC can be installed in lines to improve voltage profile.

List of Publications

International Conference

1. M. Kaur, “Newton’s Method Approach for Security Constrained OPF using TCSC,” accepted and presented in *IEEE 1st International Conference on Power Electronics, Intelligent Control and Energy Systems*, July 2016.

International Journal

1. M. Kaur and S. K. Jain, “Security Constrained OPF and Optimal Placement of TCSC using Particle Swarm Optimization,” communicated to *Electric Power Systems Research*, ISSN: 0378-7796, listed in SCI.

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Appendix A- Generator Data

Test System I: IEEE 14-bus System

Table 1: Cost Coefficients and Generator limits for IEEE 14-bus

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

Test System II: IEEE 30-bus System

Table 2: Cost Coefficients and Generator limits for IEEE 30-bus

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

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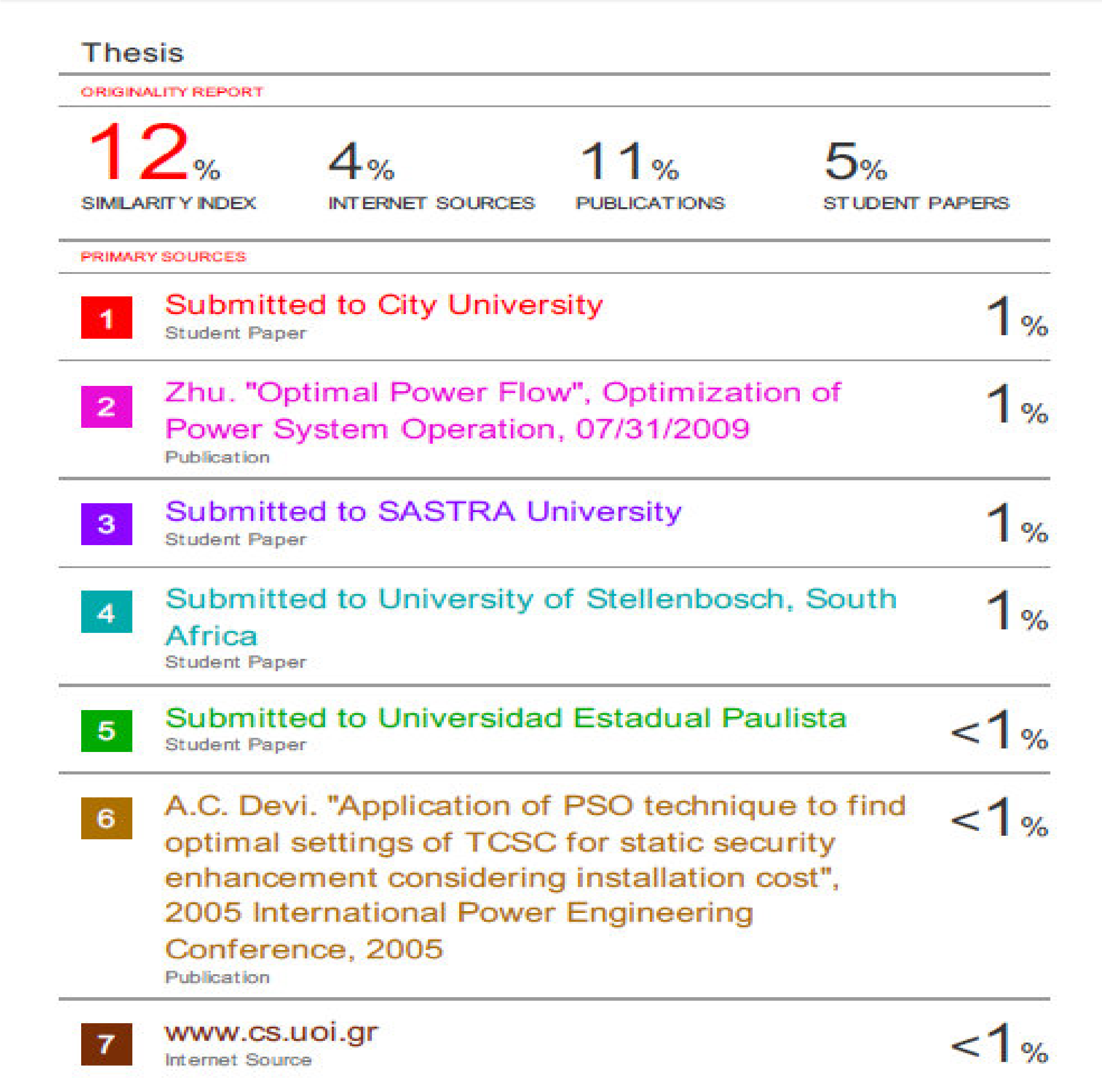

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