# INVESTIGATION OF OPTIMAL POWER FLOW WITH TCSC USING DIFFERENTIAL EVOLUTION

*Dissertation submitted in partial fulfillment of the requirements for the award of the degree of*

**MASTER OF ENGINEERING**

*in*

**POWER SYSTEMS & ELECTRIC DRIVES**

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# CERTIFICATE

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I hereby certify that the work which is being presented in dissertation entitled, **"Investigation Of Optimal Power Flow With TCSC Using Differential Evolution"**, in partial fulfillment of the requirement for the award of degree of Master of Engineering in *Power Systems & Electric Drives* submitted in *Electrical and Instrumentation Engineering Department* of Thapar University, Patiala is an authentic record of my own work carried out under the supervision of ***Ms. Manbir Kaur*** and refers other researcher's work which are duly listed in the reference section. The matter embodies in this dissertation has not been submitted for the award of any other degree to any other university, except as reported in text and references.

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Date: 15th july 2013

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

Optimal Power Flow (OPF) plays an important role in power system operation and planning. The OPF mainly aims to optimize the selected objective function such as fuel cost, active power loss via optimal adjustment of power system control variables, while at the same time satisfying various equality and inequality constraints. In recent years, FACTS devices have opened a new world in power system control. They have made the power systems operation more flexible and secure. In the power flow studies, circuit impedance, voltage magnitude and phase angle are important parameters. In this dissertation work, the TCSCs are incorporated using reactance model at fixed locations and power flow studies are carried out using Newton Raphson method. Differential evolution strategy is used to optimize the parameters like bus voltages, angles, generation cost and the reactance values of TCSC. The proposed strategy which is best suited for solving non-convex optimization problems, has been implemented on IEEE 14 bus system and it shows better results when compared with conventional iterative procedure.

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| | |
|---|---|
| IPM | Interior point method |
| GA | Genetic Algorithm |
| EP | Evolutionary programming |
| FACTS | Flexible AC Transmission Systems |
| DE | Differential Evolution |
| OPF | Optimal Power Flow |
| TCSC | Thyristor-controlled series capacitor |
| TCPAR | Thyristor controlled phase angle regulator |
| UPFC | Unified power flow controller |
| NLP | Non linear programming |
| LTP | Load Tap changing |
| TCR | Thyristor controlled reactor |
| VAR | Volt Ampere Reactive |
| SVC | Static VAR compensator |
| TSC | Thyristor Switched Capacitor |
| TSSC | Thyristor Switched Series Capacitor |
| TCSR | Thyristor controlled Series Reactor |
| TSSR | Thyristor Switched Series Reactor |
| SSSC | Static Synchronous Series Compensator |
| SMIB | Single Machine Infinite Bus |
| PSO | Particle swarm optimization |
| DE | Differential evolution |
| NP | Population Size |
| F | Mutation factor |
| CR | Crossover Rate |

# CHAPTER 1

# INTRODUCTION

## 1.1 Overview

Optimal power flow (OPF) is a static nonlinear programming problem which optimizes a certain objective function while satisfying a set of physical and operational constraints imposed by equipment limitations and security requirements. Over the last three decades, many successful methods have been developed [1–3] such as, generalized reduced gradient method, successive linear programming, successive quadratic programming, Newton method, P–Q decomposition, interior point method (IPM), genetic algorithm (GA), evolutionary programming (EP). In the deregulated power industry, private power producers are increasing rapidly to meet the increase demand and to improve the quality of power with less cost. The purpose of the transmission network is to pool power plants and load centres in order to supply the load at a required reliability, maximum efficiency and at lower cost. As power transfer increases, the power system becomes increasingly more difficult to operate and insecure with unscheduled power flows and higher losses. Rapid development of self-commutated semiconductor devices has made it possible to design power electronic equipment. This equipment is well known as flexible ac transmission system (FACTS) which has been introduced by Hingorani [4] in 1988. The objective of FACTS devices is to control power flow so that it flows through the designated routes, increase transmission line capability to its maximum thermal limit, and improve the security of transmission system with minimal infrastructure investment and environmental impact. By using FACTS devices [5] it is possible to control voltage magnitude and phase angle at chosen buses and/or line impedance of a transmission system. For last two decades researchers developed algorithms to solve optimal power flow incorporating FACTS devices. Taranto et al. [6] have proposed decomposition method to solve optimal power flow dispatch problem incorporating FACTS devices. This method can deal with the representation of series compensators and phase shifters but this method did not consider the specified line flow constraints. Gotham and Heydt [7] have presented the modeling of FACTS devices for power flow studies and the role of that modeling in the study of FACTS devices. Linear programming based security-constrained optimal power flow method [8] has been successfully used to determine the FACTS parameters to control the power flow in the specific lines. Ambriz-Perez et al. [9]

have solved optimal power flow problem incorporating FACTS devices using Newton's method, leading to highly robust iterative solutions. M. Basu [10] has proposed paper differential evolution (DE) for solving OPF problem incorporating FACTS devices. Thyristor-controlled series capacitor (TCSC) and thyristor-controlled phase shifter (TCPS) has been integrated in OPF by using the reactance model and the injected power model, respectively.

## 1.2 Literature Survey

From past many decades, research has been in progress to achieve new heights in the area of optimal operation of power system.

Happ [11] has introduced a first comprehensive survey regarding optimal power flow and presented an economic dispatch procedure for allocating generation in a power system by the use of the Jacobian matrix.

IEEE working group [12] has presented bibliography survey of major economic-security functions in 1981.

J.A. Momoh *et al.* [13] have presented a review of some selected optimal power flow techniques ranging from linear programming to artificial intelligent techniques..

T.S. Chung *et al.* [14] have presented a new approach for minimizing line losses and finding the optimal capacitor allocation in a distribution system.

E. Lobato *et al*. [15] has presented a mixed-integer linear programming optimal power flow and minimizing transmission losses and generator reactive outputs.

F. Lima *et al.* [16] have presented mixed integer linear programming (MILP) to conduct a preliminary design study on the combinatorial optimal placement of thyristor controlled phase shifter transformers (TCPSTs) in large-scale power systems.

N. Grudinin [17] has proposed a bi-criterion reactive power optimization model that represents compromise between economical and security objective functions and the optimisation problem is solved by quadratic programming.

X. Lin *et al.* [18] have presented a methodology for reactive power dispatch with consideration of the voltage stability problem. It solves both voltage stability and minimum reactive cost requirements in one unified optimisation model

A.Berizzi *et al.* [19] have presented Security Constrained Optimal Power Flow (SCOPF) to determine optimal setting and operation mode of UPFC and TCPAR.

D.Pudjianto *et al.* [20] have used linear programming and non-linear programming(NLP) based reactive OPF for allocating (auctioning) reactive power among competing generators in a deregulated environment. It has been concluded that NLP offers a faster computation speed and accuracy for the solution but the convergence could not be guaranteed for every condition.

Sergio Granville [21] has presented an implementation of an interior point method to the optimal reactive dispatch problem.

Whei-Min Lin *et al.* [22] have presented the formulation of AC optimal power flow (OPF) with deregulation issues and the effect of flexible AC transmission systems (FACTS) devices. Test results have suggested that the incorporation of FACTS devices can not only utilize the existing lines, but also reduce load curtailment and increase market profit.

Ding Xiaoying *et al.* [23] have presented an Interior Point Branch and Cut Method (IPBCM) for decoupled OPF problem. However, the proposed algorithm fails in dealing with degenerate problem.

Wei Yan *et al.* [24] have presented a new optimal reactive power flow (ORPF) model in rectangular form. In this model, the load tap changing (LTC) transformer branch is represented by an ideal transformer and its series impedance with a dummy node located between them.

N.I.Santoso *et al.* [25] have presented an expert system using a two-stage artificial neural network to control in real time the multi-tap capacitors installed on a distribution system for a nonconforming load profile such that the system losses are minimized. It has been concluded that the method requires much less computation time if compared with that for an optimization process.

Ramesh *et al.* [26] have presented a fuzzy logic approach for the contingency constrained OPF problem formulated in a decomposed form that allows for post-contingency corrective rescheduling.

Chung *et al.* [27] have presented a hybrid genetic algorithm (GA) method to solve optimal power flow (OPF) in power system incorporating Flexible ac transmission systems (FACTS). The optimal control parameter selection of two types of FACTS devices-namely, TCPS and TCSC-using the integrated GA approach have been demonstrated.

Cai *et al.* [28] have proposed the optimal choice and allocation of various types of FACTS devices in multi-machine power systems using genetic algorithm.

Mori *et al.* [29] have presented a parallel-tabu-search based method for maximizing the available transfer capability with the FACTS devices.

Somasundaram *et al.* [30] have presented an algorithm for solving security constrained optimal power flow problem through the application of evolutionary programming (EP). The security constrained optimal power flow results obtained using EP have been reported better than those obtained using conventional security constrained optimal power flow.

Ongsakul *et al.* [31] have proposed an evolutionary programming (EP) to determine the optimal allocation of FACTS devices for maximizing the total transfer capability (TTC) of power transactions between source and sink areas in deregulated power system.

Yoshida *et al.* [32] have presented a particle swarm optimization (PSO) method for reactive power and voltage control (Volt/Var Control: VVC) considering voltage security assessment (VSA) through a continuation power flow (CPFLOW) and a voltage contingency analysis technique.

M.Saravanan *et al.* [33] has presented the application of particle swarm optimization (PSO) technique to find the optimal location of flexible AC transmission system (FACTS) devices with minimum cost of installation of FACTS devices and to improve system load-ability (SL). Three types of FACTS devices, thyristor controlled series compensator (TCSC), static VAR compensator (SVC) and unified power flow controller (UPFC) have been considered.

## 1.3 Scope of Work

There are two main objectives of the work carried out:

1. To formulate the optimal flow problem incorporating TCSC device as an optimisation problem
2. To solve the formulated optimisation problem using the Differential Evolution.
3. To implement the proposed solution methodology on IEEE 14 bus system.

## 1.4 Organisation of the Dissertation

Chapter 1: It deliberates on the overview of the problem, brief literature review, scope and contribution of the Dissertation.

Chapter 2: It deliberates on the approach of optimal power flow, FACTS devices and methods of reactive power compensation for voltage control.

Chapter 3: It includes the overview of Differential Evolution, its advantages, disadvantages and its fundamental algorithm.

Chapter 4: It includes the problem formulation and results corresponding to that.

Chapter 5: It summarizes conclusion and scope for future work.

# CHAPTER 2

# OPTIMAL POWER FLOW

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## 2.1 Introduction

The operation of power industry is strongly influenced due to competitive nature of its market. Optimization methods have been widely used in power system operation, analysis and planning. Optimal power flow (OPF) mainly aims to optimize the selected objective function such as fuel cost, active power loss via optimal adjustment of power system control variables, keeping the equality and inequality constraints within limit. Equality constraints are basically the power flow equations, while inequality constraints are the limits on control variables that include the generator active powers, the generator bus voltage magnitudes, the transformer tap settings and reactive power of VAR sources. Mathematically, OPF is modelled as a nonlinear programming (NLP) problem, which usually minimizes the total generating unit fuel cost and total load bus voltage deviation from a specified point subject to a set of equality and inequality constraints and thus losses can be reduced to a significant amount . The current scenario indicates that the demand for the power transfer is increasing day by day, the power system becomes increasingly more difficult to operate and insecure with unscheduled power flows and thus handling the losses. Rapid development of self-commutated semiconductor devices has made it possible to design power electronic equipment. This equipment is well known as flexible ac transmission system (FACTS) which has been introduced by Hingorani [4] in 1988. FACTS Technology is concerned with the management of active and reactive power to improve the performance of electrical networks and thus minimizing the losses. FACTS includes various types of series and shunt type VAR compensators. Series and shunt VAR compensators have the capability to change the performance characteristics of electrical networks. In both of them, the reactive power through the system can significantly improve the performance of the power system. So, as discussed earlier OPF is modelled as a nonlinear programming (NLP) problem and when we incorporated FACTS in it and considered as a control variable, it becomes even more nonlinear and complex. Various researchers developed algorithms to solve optimal power flow incorporating FACTS devices. T.S.Chung *et al.* [8] presented a Hybrid Genetic Algorithm (GA) method to solve OPF incorporating FACTS devices. GA is integrated with conventional OPF to select the best control parameters to minimize the total generation fuel cost and keep the power flows within the security limits. TCPS and TCSC are modeled. The proposed method was applied on modified IEEE 14 bus system and it converged in a few iterations. L.J.Cai *et al.* [28] proposed optimal choice and allocation of FACTS devices in multi-machine power systems using genetic algorithm. The objective is to achieve the power system economic generation allocation and dispatch in deregulated electricity market. The locations of the FACTS devices, their types and ratings are optimized simultaneously. UPFC, TCSC, TCPST and SVC are modeled and their investment costs are also considered.

## 2.2 Load Flow Analysis

Power flows studies, commonly referred to as *load flow*, are the backbone of power system analysis and design. They are necessary for planning, operation, economic scheduling, exchange of power between utilities and for other analyses such as transient stability and contingency studies.

The voltages and power flows in an electrical system can be determined for a given set of loading and operating conditions. This is known as the *power flow* problem. In power flow analysis, it is normal to assume that the system is balanced and that the network is composed of constant, linear, lumped-parameter branches. (In the most basic form of the power flow, transformer taps are assumed to be fixed). However, because the injection/demand at bus-bars is generally specified in terms of real and reactive power, the overall problem is nonlinear. Accordingly, the power flow problem is a set of simultaneous nonlinear algebraic equations what are solved by numerical techniques like:

*1. GAUSS-SEIDEL METHOD*

*2. NEWTON RAPHSON METHOD*

*3. DECOUPLED FLOW METHOD*

*3. FAST DECOUPLED FLOW METHOD*

### 2.2.1 Need of Load Flow Study

Load flow study in power system is the steady state solution of power system network .The power system is modelled as an electric network and is solved for steady state powers and voltages at various buses .The direct analysis of circuits is not possible as the loads are given in terms of complex powers rather than impedances and the generators behaves more like power source than voltage source.

### 2.2.2 Significance of Load Flow Study

1. To determine current, voltage, active power, reactive power etc. at various buses in power system operating under normal steady state.

2. To plan best operation and control of existing system.
3. To plan future expansion to keep pace with load growth.
4. To help in ascertaining the effect of new load, new generating stations, new lines and new interconnections before they are installed.
5. Due to this information system losses are minimized and also check is provided on system stability.
6. To provide the proper pre-fault power system analysis to avoid system outage due to fault.

### 2.2.3 Choice of Variables

Load-flow analysis deals with known real and reactive power flows at each bus, and those voltage magnitudes that are explicitly known, and from this information calculating the remaining voltage magnitudes and all the voltage angles. To summarize, our three types of buses in load flow analysis are PQ (load bus), PV (generator bus), and θ V (slack bus). Given these two input variables per bus, and knowing all the fixed properties of the system (i.e., the impedances of all the transmission links, as well as the AC frequency), we can find values for all the variables that were not originally specified for each bus: θ and V for all the PQ buses; θ and Q for the PV buses; and P and Q for the slack bus. The known and unknown variables for each type of bus are shown in table 2.1

Table 2.1: Variables in Power Flow Analysis

| Types of Bus | Variables  Given (Knowns) | Variables Found (Unknowns) |
|---|---|---|
| Generator | Real Power (P)<br>Voltage magnitude (V) | Voltage angle (θ)<br>Reactive Power (Q) |
| Load or Generator | Real Power (P)<br>Reactive power (Q) | Voltage angle (θ)<br>Voltage magnitude (V) |
| Slack | Voltage angle (θ)<br>Voltage magnitude (V) | Real power (P)<br>Reactive power (Q) |

### 2.2.4 Power Flow Equation

Typical bus of a power system network shown as in figure 2.1 as

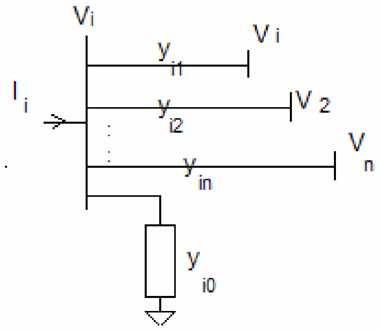


Figure 2.1 Typical bus of a power system network

Applying kirchoff's current law at this node

$I_i = (y_{i0} + y_{i1} + y_{i2} \ldots\ldots\ldots\ldots + y_{in})V_i - y_{i1}V_1 - y_{i2}V_2 \ldots\ldots\ldots\ldots - y_{in}V_n$...................(1.1)

$I_i = V_i\sum_{j=0}^{n} y_{ij} - \sum_{j=0}^{n} y_{ij}V_j$ where $j \neq i$......................................................................(1.2)

$$P_i + jQ_i = V_iI_i^*$$

Substituting $I_i$ from above equation into 2

$(P_i - jQ_i) / V_i^* = V_i\sum_{j=0}^{n} y_{ij} - \sum_{j=0}^{n} y_{ij}V_j$ where $j \neq i$......................................................(1.3)

Equation 2 can be written as below

$I_i = \sum y_{ij}V_j$

Above equation in polar form

$$I_i = \sum |Y_{ij}||V_j|\angle\theta_{ij} + \delta_{ij}$$

The complex power at bus i is

$$P_i - jQ_i = V_{i^*}I_i$$

Subsituting value of $I_i$ in above equation is

$$P_i - jQ_i = |V_i|\angle{-\delta_i}\sum |\, Y_{ij} \,|\angle\theta_{ij} + \delta_{ij}$$

Separating real and imaginary parts

$P_i = \sum_{j=1}^{n} |V_i||V_j|| Y_{ij} |\cos(\theta_{ij} - \delta_i + \delta_j)$................................................................(1.4)

$Q_i = -\sum_{j=1}^{n}|V_i||V_j||Y_{ij}|\sin(\theta_{ij} - \delta_i + \delta_j)$................................................................(1.5)

Above two equations constitute a set of non linear algebraic equations in terms of independent variables, voltage magnitude in per unit, and phase angle in radians. Expanding above two equations in Taylor series about initial estimate and neglecting all higher order terms results inset of equations of short form is given as follows:

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix}J_1 & J_2\\ J_3 & J_4\end{bmatrix}\begin{bmatrix}\Delta V\\ \Delta\delta\end{bmatrix}$$

The diagonal and off diagonal elements of $J_1$ are

$\frac{\partial P_i}{\partial \delta_i} = \sum_{j\neq i}^{n}|V_i||V_j||Y_{ij}|\sin(\theta_{ij} - \delta_i + \delta_j)$ .............................................................(1.6)

$\frac{\partial P_i}{\partial \delta_j} = -|V_i||V_j||Y_{ij}|\sin(\theta_{ij} - \delta_i + \delta_j)$ $\quad j \neq I$.....................................................(1.7)

The diagonal and off diagonal of $J_4$ are

$$\frac{\partial Q_i}{\partial |V_i|} = -2V_iY_{ii}\sin\theta_{ii} - \sum_{j=i}^{n} V_iY_{ij}\sin(\theta_{ij} - \delta_i + \delta_j) \text{..........................................(1.8)}$$

$$\frac{\partial Q_i}{\partial |V_j|} = -V_iY_{ij}\sin(\theta_{ij} - \delta_i + \delta_j) \text{..............................................................................(1.9)}$$

The terms $\Delta Pi^{(k)}$ and $\Delta Qi^{(k)}$ are the differences between the scheduled and calculated values,termed as power residuals, given by

$\Delta Pi^{(k)} = Pi^{(sch)} - Pi^{(k)}$ ...................................................................................(1.10)

$\Delta Qi^{(k)} = Qi^{(sch)} - Qi^{(k)}$.....................................................................................(1.11)

The new estimates for bus voltages are

$\delta i^{(k+1)} = \delta i^{(k)} + \Delta\delta i^{(k)}$..........................................................................................(1.12)

$|Vi^{(k+1)}| = |Vi^{(k)}| + \Delta|Vi^{(k)}|$..................................................................................(1.13)

### 2.2.5 Algorithm for Newton Raphson method of Load Flow Analysis

The procedure for power flow solution by the Newton-Raphson method is as follows:

1. For load buses , where $Pi^{(sch)}$ and $Qi^{(sch)}$ are specified, voltage magnitudes and phase angles are set equal to the slack bus values , or 1.0 and 0.0, i.e., $|Vi^{(0)}| = 1.0$ and $\delta i^{(0)} = 0.0$. For voltage-regulated buses, where |Vi| and $Pi^{(sch)}$ are specified, phase angles are set equal to the slack bus angle, or 0, i.e., $\delta i^{(0)} = 0$.
2. For load buses, $Pi^{(k)}$ and $Qi^{(k)}$ are calculated from (4)and (5)and $\Delta Pi^{(k)}$ and $\Delta Qi^{(k)}$ are calculated (10) and (11).
3. For voltage-controlled buses, $Pi^{(k)}$ and $\Delta Pi^{(k)}$ are calculated from (4) and (10), respectively.
4. The elements of the Jacobian matrix ($J_1$,$J_2$,$J_3$ and $J_4$) are calculated from (6)- (8).
5. The linear simultaneous equation is solved directly by optimally ordered triangular factorization and Gaussian elimination.
6. The new voltage magnitudes and phase angles are computed from equations (12) and (13).
7. The process is continued until the residuals $\Delta Pi^{(k)}$ and $\Delta Qi^{(k)}$ are less than the specified accuracy i.e.,

$$|\Delta Pi(k)| <= \varepsilon$$

$$|\Delta Qi(k)| <= \varepsilon$$

## 2.3 FACTS Devices

Flexible AC Transmission System (FACTS) is defined by IEEE as “Alternating current transmission systems incorporating power electronic-based and other static controllers to enhance controllability and increase power transfer capability.”

In the past few years the demand for electrical energy has increased significantly and as a result energy transmission systems are facing power transmission limitation crisis. The limitations occur due to keeping a balance between maintaining stability and supplying the allowed level of voltage. As a result of this the practical operation capacity of the system is far less than the real capacity. This results in non-optimal operation of the energy transmission systems. One among the solutions to this problem of increasing power transmission capacity is construction of new transmission lines. This is not feasible both economically and practically.

The development of power electronics leads to introduction to the use of flexible ac transmission system (FACTS) controllers in power systems in a very fast manner and afford unique control flexibility and versatility. They are used to enhance the real capacity of transmission lines without having to construct any new transmission lines. These features of FACTS can be exploited to improve the voltage stability, and steady state and transient stabilities of a complex power system. Their ability to improve damping and to control the flow of power through selected corridors in a network is also advantageous. Certain system variables (such as power flows) which are normally not controllable can now be now independently adjusted using this extra flexibility.

Controllable parameters and the manner, in which they are realized electronically, can be used to differentiate FACTS devices. Thus, devices exist which can control line series or shunt reactance**,** phase-shifting transformer angle or combinations of these**.** Other devices inject controllable voltages in series or in parallel with the line being compensated [5].

## 2.4 Methods of Compensation

There are various methods of compensation by which we can control the desired variables. Depending on our requirement these devices are categorised into different type of classes, so that we can easily differentiate when required.

### 2.4.1 Shunt Connected Controllers

Shunt Controllers are available in many packages like variable impedance, variable source, or a combination of these. All shunt Controllers works on same principle of injecting current into the system at the point of connection. Moreover, variable shunt impedance connected to the line voltage causes a variable current flow and hence represents injection of current into the line. As long as the injected current is in phase quadrature with the line voltage, the shunt

Controller only supplies or consumes variable reactive power. Any relationship other than this will involve handling of real power as well. Fig.2.2 shows the shunt connected controller.

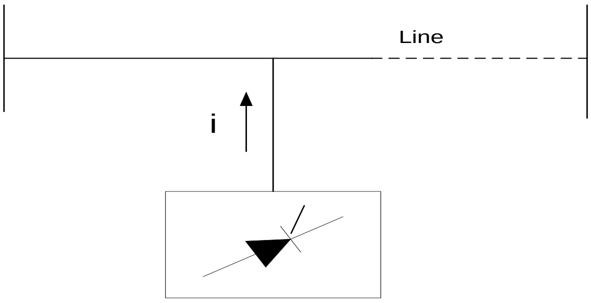


**Fig.2.2 Shunt Connected Controller**

### **2.4.1.1 Static VAR Compensator** (SVC)

SVC is a shunt connected static VAR absorber or generator whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the electrical power system (typically bus voltage). This is a first generation FACTS device that can be used for improving the voltage profile of the system by controlling voltage at the required bus. Thyristor-controlled or thyristor-switched reactor, and/or thyristor-switched capacitor or combinations are generally referred by this term. SVC is based on thyristors without the gate turn-off capability. It includes separate equipment for leading and lagging vars; the thyristor-controlled or thyristor-switched reactor for absorbing reactive power and thyristor-switched capacitor for supplying the reactive power. SVC as compared to STATCOM, by some is considered as a lower cost alternative, but if the comparison is made based on the required performance and not just the MVA size, SVC may not be the best case. Maintaining the voltage at a particular bus by means of reactive power compensation (obtained by varying the firing angle of the thyristors) is the primary task of SVC. High performance steady state and transient voltage control compared with classical shunt compensation are the reasons for its use. SVCs are also used to damping power swings, improve transient stability, and reduce system losses by optimized reactive power control. An alternative SVC model, which circumvents the additional iterative process, consists in handling the TCR firing angle α as a state variable in power flow formulation [34]. The variable will be designated here as $\alpha_{SVC}$. The reactive power at bus k can be given as

$$Q_k = \frac{-V_k^2}{X_c X_l}\left\{ X_l - \frac{X_c}{\pi}\left[2(\pi - \alpha_{SVC}) + \sin(2\alpha_{SVC})\right] \right\} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1.14)$$

### **2.4.1.2 Thyristor Controlled Reactor** (TCR)

TCR is basically a shunt-connected, thyristor-controlled inductor whose effective reactance is varied in a continuous manner by partial-conduction control of the thyristor valve. TCR is a subset of SVC in which a thyristor-based ac switch with firing angle control.is basically used for controlling conduction time and hence, current in a shunt reactor.

#### 2.4.1.3 Thyristor Switched Reactor (TSR)

It is a shunt-connected, thyristor-switched inductor whose effective reactance is varied in a stepwise manner by full- or zero-conduction operation of the thyristor valve. TSR is another subset of SVC. TSR is made up of several shunt connected inductors which are switched in and out by thyristor switches without any firing angle controls in order to achieve the required step changes in the reactive power consumed from the system. Use of thyristor switches without firing angle control results in lower cost and losses, but without a continuous control.

#### 2.4.1.4 Thyristor Switched Capacitor (TSC)

It is a shunt-connected, thyristor-switched capacitor whose effective reactance is varied in a stepwise manner by full or zero conduction operation of the thyristor valve. TSC is also a subset of SVC in which thyristor based ac switches are used to switch in and out (without firing angle control) shunt capacitors units, in order to achieve the required step change in the reactive power supplied to the system. Unlike shunt reactors, shunt capacitors cannot be switched continuously with variable firing angle control.

#### 2.4.1.5 Static Synchronous Compensator

(STATCOM) is basically a static synchronous generator operated as a shunt shunt-connected static VAR compensator whose capacitive or inductive output current can be controlled independent of the ac system voltage. It can be based on a voltage sourced or current-sourced converter. As mentioned before, from an overall cost point of view, the voltage-sourced converters seem to be preferred, and will be the basis for presentations of most converter-based FACTS Controllers.

For the voltage-sourced converter, its ac output voltage is controlled such that it is just right for the required reactive current flow for any ac bus voltage dc capacitor voltage is automatically adjusted as required to serve as a voltage source for the converter. STATCOM can be designed to also act as an active filter to absorb system harmonics.

STATCOM as defined above by IEEE is a subset of the broad based shunt connected Controller which includes the possibility of an active power source or storage on the dc side so that the injected current may include active power. Equivalent Circuit of STATCOM is shown in fig 2.3.

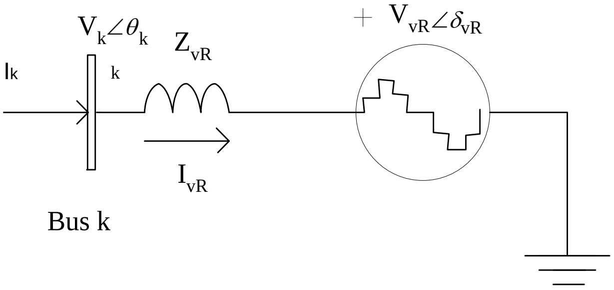


Figure 2.3 Equivalent circuit of STATCOM

The active and reactive power equations for the converter and bus k can be written as [35]

$P_{vR} = V_{vR}^2 G_{vR} + V_{vR}V_k[G_{vR}\cos(\delta_{vR} - \theta_k) + B_{vR}\sin(\delta_{vR} - \theta_k)]$……………………..……(1.15)

$Q_{vR} = -V_{vR}^2 B_{vR} + V_{vR}V_k[G_{vR}\sin(\delta_{vR} - \theta_k) - B_{vR}\cos(\delta_{vR} - \theta_k)]$…………………...(1.16)

$P_k = V_k^2 G_{vR} + V_{vR}V_k[G_{vR}\cos(\theta_k - \delta_{vR}) + B_{vR}\sin(\theta_k - \delta_{vR})]$……………......................(1.17)

$Q_k = -V_k^2 B_{vR} + V_{vR}V_k[G_{vR}\sin(\theta_k - \delta_{vR}) - B_{vR}\cos(\theta_k - \delta_{vR})]$……………………..(1.18)

### 2.4.2 Series Connected Controllers

The series Controller could be variable impedance, such as capacitor, reactor, etc., or power electronics based variable source of main frequency, sub-synchronous and harmonic frequencies (or a combination) to serve the desired need. In principle, all series Controllers inject voltage in series with the line. Even variable impedance multiplied by the current flow through it, represents an injected series voltage in the line. As long as the voltage is in phase quadrature with the line current, the series Controller only supplies or consumes variable reactive power. Any other phase relationship will involve handling of real power as well.

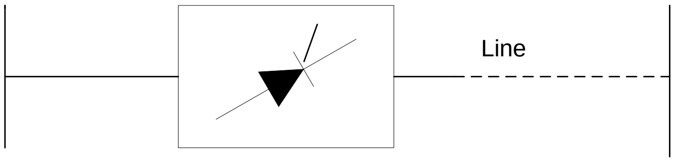


Figure 2.4 Series Connected Controller

#### 2.4.2.1 Thyristor Controlled Series Capacitor (TCSC)

It is a capacitive reactance compensator which consists of a series capacitor bank shunted by a thyristor-controlled reactor in order to provide a smoothly variable series capacitive reactance. It is an alternative to SSSC above and like an SSSC; it is a very important FACTS Controller. A variable reactor such as a Thyristor-Controlled Reactor (TCR) is connected across a series capacitor. When the TCR firing angle is 180 degrees, the reactor becomes non-conducting and the series capacitor has its normal impedance. As the firing angle is advanced from 180 degrees to less than 180 degrees, the capacitive impedance increases. At the other end, when the TCR firing angle is 90 degrees, the reactor becomes fully conducting, and the total impedance becomes inductive, because the reactor impedance is designed to be much lower than the series capacitor impedance. With 90 degrees firing angle, the TCSC helps in limiting fault current. The TCSC may be a single, large unit, or may consist of several equal or different-sized smaller capacitors in order to achieve a superior performance. It is one of the important members of FACTS family that is increasingly applied with long transmission lines by the utilities in modern power systems. It can have various roles in the operation and control of power systems, such as scheduling power flow, decreasing unsymmetrical components, reducing net loss, providing voltage support, limiting short-circuit currents, mitigating sub-synchronous resonance (SSR), damping the power oscillation, and enhancing transient stability. The power flow equations can be derived from the equivalent circuit shown in fig 2.5.[10]

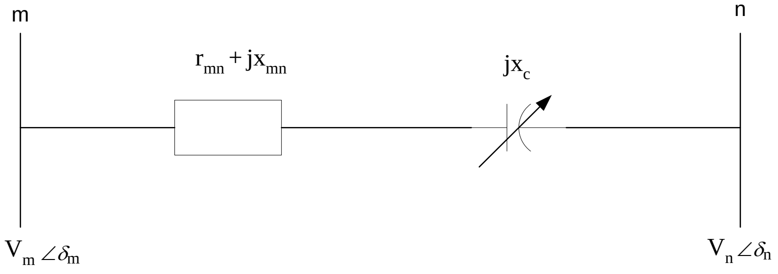


Figure 2.5 Equivalent circuit of TCSC

$$P_{mn} = V_m^2 g_{mn} - V_m V_n g_{mn} \cos(\delta_m - \delta_n) - V_m V_n b_{mn} \sin(\delta_m - \delta_n) \ldots\ldots (1.19)$$

$$Q_{mn} = -V_m^2 b_{mn} - V_m V_n g_{mn} \sin(\delta_m - \delta_n) + V_m V_n b_{mn} \cos(\delta_m - \delta_n) \ldots\ldots (1.20)$$

$$P_{nm} = V_n^2 g_{mn} - V_m V_n g_{mn} \cos(\delta_m - \delta_n) + V_m V_n b_{mn} \sin(\delta_m - \delta_n) \ldots\ldots (1.21)$$

$$Q_{nm} = -V_m^2 b_{mn} + V_m V_n g_{mn} \sin(\delta_m - \delta_n) + V_m V_n b_{mn} \cos(\delta_m - \delta_n) \ldots\ldots (1.22)$$

$$\text{where } g_{mn} = \frac{r_{mn}}{r_{mn}^2 + (x_{mn} - x_c)^2}\ ,\ b_{mn} = \frac{x_{mn} - x_c}{r_{mn}^2 + (x_{mn} - x_c)^2}$$

### 2.4.2.2 Thyristor-Switched Series Capacitor (TSSC)

It is a capacitive reactance compensator which consists of a series capacitor bank shunted by a thyristor-switched reactor to provide a stepwise control of series capacitive reactance. Instead of continuous control of capacitive impedance, this approach of switching inductors at firing angle of 90 degrees or 180 degrees but without firing angle control could reduce cost and losses of the Controller. It is reasonable to arrange one of the modules to have thyristor control, while others could be thyristor switched.

### 2.4.2.3 **Thyristor-Controlled Series Reactor** (TCSR)

TCSR is an inductive reactance compensator which consists of a series reactor shunted by a thyristor controlled reactor in order to provide a smoothly variable series inductive reactance. When the firing angle of the thyristor controlled reactor is 180 degrees, it stops conducting, and the uncontrolled reactor acts as a fault current limiter. As the angle decreases below 180 degrees, the net inductance decreases until firing angle of 90 degrees, when the net inductance is the parallel combination of the two reactors. As for the TCSC, the TCSR may be a single large unit or several smaller series units.

### 2.4.2.4 **Thyristor-Switched Series Reactor** (TSSR)

TSSR is an inductive reactance compensator which consists of a series reactor shunted by a thyristor-controlled switched reactor in order to provide a stepwise control of series inductive reactance. This is a complement of TCSR, but with thyristor switches fully on or off (without firing angle control) to achieve a combination of stepped series inductance.

### 2.4.2.5 **Static Synchronous Series Compensator** (SSSC)

SSSC is a member of FACTS family which is connected in series with a power system. It consists of a solid state voltage source converter which generates a controllable alternating current voltage at fundamental frequency. When the injected voltage is kept in quadrature with the line current, it can emulate as inductive or capacitive reactance so as to influence the power flow through the transmission line. While the primary purpose of a SSSC is to control power flow in steady state, it can also improve transient stability of a power system.

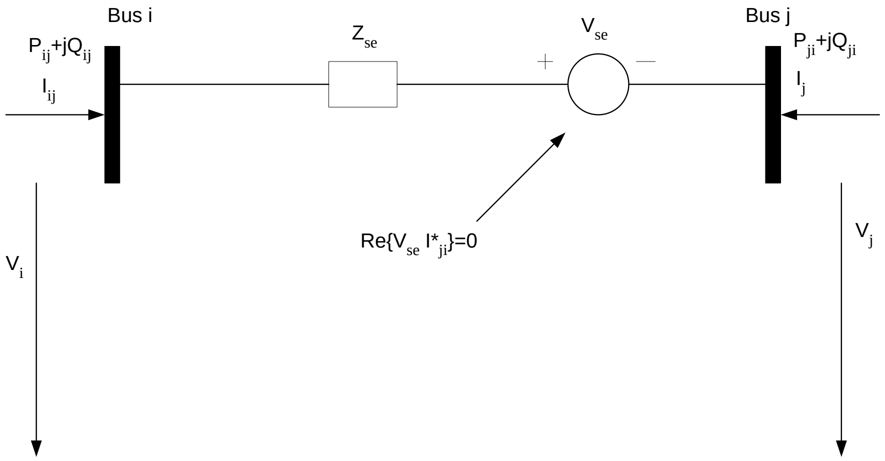


Figure 2.6 Equivalent circuit of SSSC

An equivalent circuit of the SSSC is depicted in Fig. 2.6 that can be derived based on the operation principle of the SSSC [36].

$$P_{ij} = V_i^2 g_{ii} - V_iV_j(g_{ij}cos\theta_{ij} + b_{ij}sin\theta_{ij}) - V_iV_{se}(g_{ij}\cos(\theta_i - \theta_{se}) + b_{ij}sin(\theta_i - \theta_{se}))\ldots. \quad . \quad \ldots\ldots(1.23)$$

$$Q_{ij} = V_i^2 b_{ii} - V_i V_j (g_{ij} sin\theta_{ij} + b_{ij} cos\theta_{ij}) - V_i V_{se}(g_{ij} \sin(\theta_i - \theta_{se}) - b_{ij} cos(\theta_i - \theta_{se}))\text{..}$$

….(1.24)

$$P_{ji} = V_j^2 g_{jj} - V_i V_j \left(g_{ij} cos\theta_{ji} + b_{ij} cos\theta_{ij}\right) + V_i V_{se}(g_{ij} \cos\left(\theta_j - \theta_{se}\right) + b_{ij} sin\left(\theta_j - \theta_{se}\right))\dots$$

…..(1.25)

$$Q_{ji} = V_j^2 g_{jj} - V_i V_j \left(g_{ij} cos\theta_{ij} - b_{ij} sin\theta_{ij}\right) + V_i V_{se}(g_{ij} \cos\left(\theta_j - \theta_{se}\right) - b_{ij} sin\left(\theta_j - \theta_{se}\right))\text{..}$$

…..(1.26)

where;

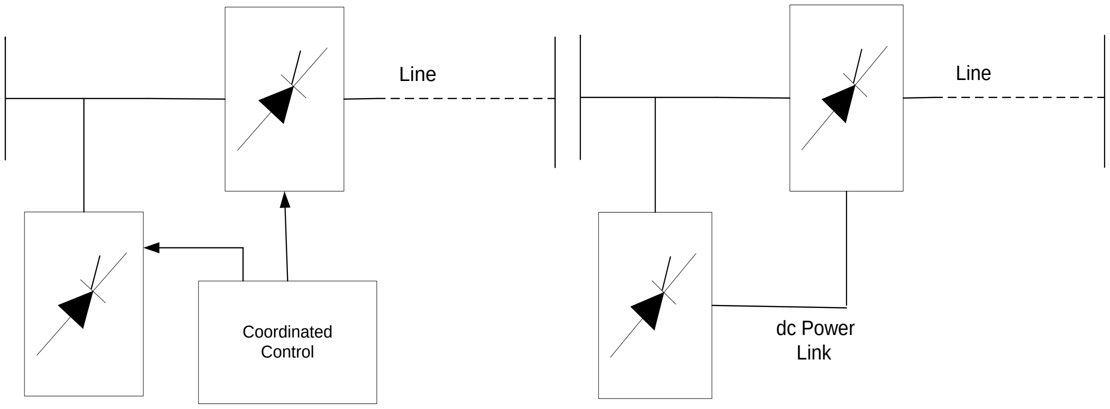
$g_{se} + jb_{se} = {}^{1}/{}_{Z_{se}}$,

$g_{ii} = g_{ij} + g_{sh}$ , $b_{ii} = b_{ij} + b_{sh}$ ,

$g_{ii} = g_{jj}$,$b_{jj} = b_{ii}$

### 2.4.3 Combined Series and Shunt Controllers

This could be a combination of separate shunt and series Controllers, which are controlled in a coordinated manner, shown in Fig.2.7 (a), or a Unified Power Flow Controller with series and shunt elements Fig.2.7 (b). In principle, combined shunt and series Controllers inject current into the system with the shunt part of the Controller and voltage in series in the line with the series part of the Controller. However, when the shunt and series Controllers are unified, there can be a real power exchange between the series and shunt Controllers via the power link.



**(a)** **(b)**

Figure.2.7 Series- Shunt controller

#### 2.4.3.1 Unified power Flow controller (UPFC)

Among the available FACTS devices, is the most versatile one that can be used to improve steady state stability, dynamic stability and transient stability. The UPFC can independently control many parameters since it is the combination of Static Synchronous Compensator (STATCOM) and SSSC. These devices offer an alternative mean to mitigate power system oscillations. It has been reported in many papers that UPFC can improve stability of single machine infinite bus (SMIB) system and multi-machine system.[37]

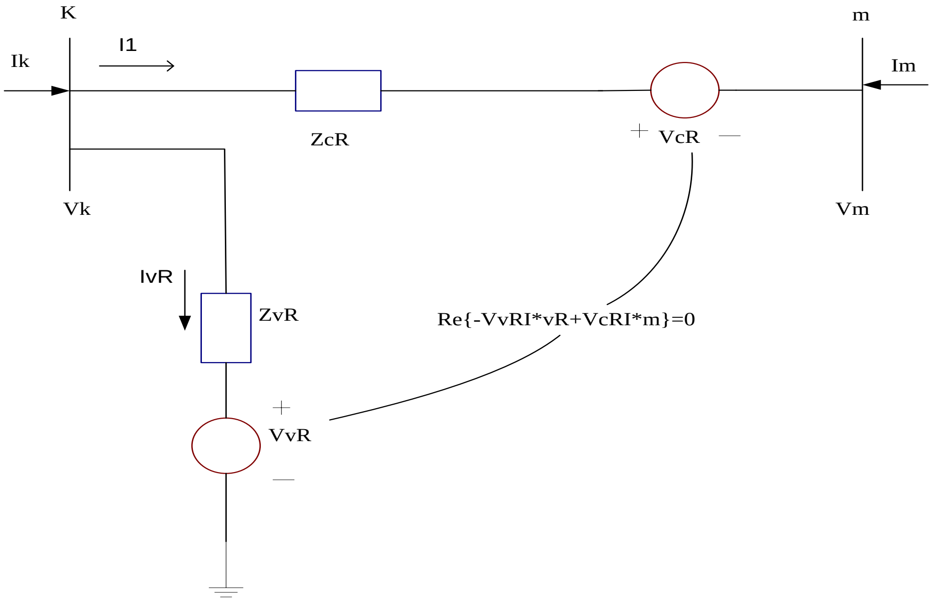


Fig 2.8 Equivalent circuit of UPFC

Based on equivalent circuit shown in Fig 2.8, the active and reactive power equations are:

At node k:

$$P_k = V_k^2 G_{kk} + V_k V_m (G_{km} \cos(\theta_k - \theta_m) + B_{km} \sin(\theta_k - \theta_m)) + V_k V_{cR} (G_{km} \cos(\theta_k - \theta_{cR}) + B_{km} \sin(\theta_k - \theta_{cR}))$$
$$+ V_k V_{vR} (G_{vR} \cos(\theta_k - \theta_{vR}) + B_{vR} \sin(\theta_k - \theta_{vR})) \quad \ldots(1.27)$$

$$Q_k = -V_k^2 B_{kk} + V_k V_m (G_{km} \sin(\theta_k - \theta_m) - B_{km} \cos(\theta_k - \theta_m)) + V_k V_{cR} (G_{km} \sin(\theta_k - \theta_{cR}) - B_{km} \cos(\theta_k - \theta_{cR}))$$
$$+ V_k V_{vR} (G_{vR} \sin(\theta_k - \theta_{vR}) - B_{vR} \cos(\theta_k - \theta_{vR})) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(1.28)$$

At node m:

$$P_m = V_m^2 G_{mm} + V_m V_k (G_{mk} \cos(\theta_m - \theta_k) + B_{mk} \sin(\theta_m - \theta_k)) + V_m V_{cR} (G_{mm} \cos(\theta_m - \theta_{cR}) + B_{mm} \sin(\theta_m - \theta_{cR}))$$
$$....(1.29)$$

$$Q_m = -V_m^2 B_{mm} + V_m V_k (G_{mk} \sin(\theta_m - \theta_k) - B_{mk} \cos(\theta_m - \theta_k)) + V_m V_{cR} (G_{mm} \sin(\theta_m - \theta_{cR}) - B_{mm} \cos(\theta_m - \theta_{cR}))$$
$$\ldots.(1.30)$$

Series converter:

$$P_{cR} = V_{cR}^2 G_{mm} + V_{cR} V_k (G_{km} \cos(\theta_{cR} - \theta_k) + B_{km} \sin(\theta_{cR} - \theta_k)) + V_{cR} V_m (G_{mm} \sin(\theta_{cR} - \theta_m) + B_{mm} \sin(\theta_{cR} - \theta_m)) \qquad \ldots\ldots(1.31)$$

$$Q_{cR} = -V_{cR}^2 B_{mm} + V_{cR} V_k (G_{km} \sin(\theta_{cR} - \theta_k) - B_{km} \cos(\theta_{cR} - \theta_k)) + V_{cR} V_m (G_{mm} \sin(\theta_{cR} - \theta_m) - B_{mm} \cos(\theta_{cR} - \theta_m)) \qquad \ldots\ldots(1.32)$$

Shunt converter:

$$P_{vR} = -V_{vR}^2 G_{vR} + V_{vR} V_k (G_{vR} \cos(\theta_{vR} - \theta_k) + B_{vR} \sin(\theta_{vR} - \theta_k)) \qquad \ldots\ldots(1.33)$$

$$Q_{vR} = V_{vR}^2 B_{vR} + V_{vR} V_k (G_{vR} \sin(\theta_{vR} - \theta_k) - B_{vR} \cos(\theta_{vR} - \theta_k)) \qquad \ldots\ldots(1.34)$$

### 2.4.4 Combines Series-Series Controllers

This could be a combination of separate series controllers, which are controlled in a coordinated manner, in a multiline transmission system, shown in Fig.2.9. Or it could be a unified Controller, Fig. 2.9, in which series Controllers provide independent series reactive compensation for each line but also transfer real power among the lines via the power link. The real power transfer capability of the unified series-series Controller, referred to as Interline Power Flow Controller, makes it possible to balance both the real and reactive power flow in the lines and thereby maximize the utilization of the transmission system.

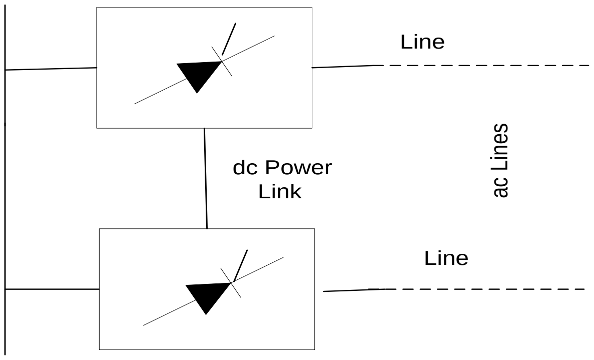


**Fig.2.9 Series-Series Controller**

Note that the term "unified" here means that the de terminals of all Controller converters are all connected together for real power transfer.

# CHAPTER 3

# DIFFERENTIAL EVOLUTION

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## 3.1 Introduction

Practical minimization technique should fulfill four requirements:

(1) Ability to handle non-differentiable, nonlinear and multimodal cost functions.

(2) Parallelizability to cope with computation intensive cost functions.

(3) Ease of use, i.e. few control variables to steer the minimization. These variables should also be robust and easy to choose.

So in order to meet above four requirements, various optimization techniques are used like Particle swarm optimization (PSO), genetic algorithms (GA), evolutionary algorithms, Ant colony algorithm etc. Differential Evolution also belongs to this family as these all are the biological inspired techniques.

## 3.2 Overview

Differential Evolution (DE) is a type of evolutionary algorithm originally proposed by Price and Storn [38] for optimization problems over a continuous domain. DE is exceptionally simple, significantly faster and robust. The basic idea of DE is to adapt the search during the evolutionary process. Differential Evolution (DE) is a parallel direct search method which utilizes NP D-dimensional parameter vectors $P_{ij}$, i = 1, 2, . . . .NP as a population for each generation G. NP does not change during the minimization process. The initial vector population is chosen randomly and should cover the entire parameter space. At the start of the evolution, the perturbations are large since parent populations are far away from each other. As the evolutionary process matures, the population converges to a small region and the perturbations adaptively become small. As a result, the evolutionary algorithm performs a global exploratory search during the early stages of the evolutionary process and local exploitation during the mature stage of the search. In DE the fittest of an offspring competes one-to-one with that of corresponding parent which is different from other evolutionary algorithms. This one-to-one competition gives rise to faster convergence rate. Price and Storn gave the working principle of DE with simple strategy in [38]. Later on, they suggested ten different strategies of DE [39]. The key parameters of control in DE are population size (NP), scaling or mutation factor (F) and crossover constant (CR). The optimization process in DE is carried out with three basic operations: mutation, crossover and selection. The DE algorithm is described as follows:

### 3.2.1 Initialization

The basic step in DE optimization is to create an initial population of candidate solutions by assigning random values to each decision parameter of each individual of the population. A population P consisting of $N_P$ individuals is constructed in a random manner such that the value lies within the feasible bounds $P_j^{min}$ and $P_j^{max}$ of the decision variable, according to the following rule:

$$P_{ij}^{t} = P_j^{min} + rand \times \left(P_j^{max} - P_j^{min}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.1)$$

Where i= 1, 2,..…, $N_P$ Denotes the individual’s population index

j=1, 2,….,D Signifies the D-dimensional search space position

$P_j^{min}$ =Lower bound of the decision variable

$P_j^{max}$ =Upper bound of the decision variable

$rand$ = A uniformly distributed random number varies between 0 to 1

### 3.2.2. Mutation

A new population named mutant population is generated whose size is same as that of the initial population Np. Among the various strategies used for mutation in DE, the addition of the weighted difference vector between the two population members to the third member is adopted in this approach. Here three different members namely $P_{r1}$ ,$P_{r2}$ and $P_{r3}$ are chosen from the current population .Then the difference between any two of these members is scaled by a scalar number F, which is then added to the third member. The value of F is usually in between 0.4 and 1. The Mutation operation using the difference between two randomly selected individuals may cause the mutant individual to escape from the search domain. If an optimized variable for the mutant individual is outside of the domain search, then this variable is replaced by its lower bound or its upper bound so that each individual can be restricted to remain within the search domain. In each generation, a donor vector is created in order to change the population member vector. Therefore the j$^{th}$ member of the donor vector $V_{ij}(t)$ is expressed as

$$V_{ij}^{(t+1)} = P_{r1}j(t) + F * (P_{r2}j(t) - P_{r3}j(t)) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.2)$$

### 3.2.3. Crossover

In order to increase the diversity of the perturbed parameter vectors, crossover is introduced. A new population is created by suitably combining the parent population and the mutant population. The process of crossover is based on the CR which is in between (0,1). Binomial crossover scheme is used which is performed on all D variables and can be expressed as:

$$U_{i,j}^{t+1} = V_{i,j}^{t+1} \quad \text{if rand } (0, 1) < \text{CR}$$

$$U_{i,j}^{t+1} = P_{i,j}^{t+1} \quad \text{else}$$

where $U_{ij}(t)$ is the child which is obtained after crossover operation where i = 1,2, ... Np, j = 1,2, ..... D. Here, rand ensures that the newly generated vector is different for both $V_{ij}(t)$ and $P_{ij}(t)$ .

### 3.2.4. Selection

After calculating the objective function F(t) using D number of variables for using initial and crossover population , a new population with the least objective function ( minimum fuel cost) is formed for the next generation. This is given by

$$P_i^t = \begin{cases} U_i^{t+1}, if\ f(U_i^{t+1}) \le f(P_i^t) \\ P_i^t, \qquad otherwise \end{cases}$$

The process is repeated until the maximum number of generations or no improvement is seen in the real power generation cost after many generations. The global optimum searching capability and the convergence speed of DE are very sensitive to the choice of control parameters NP, F and CR. The crossover $_{\text{rate}}$ CR is between [0.3, 0.9]. Mutation Factor (F) should not be smaller than a certain value to prevent premature convergence.

### 3.2.5 Verification of the Stopping Criterion

Set the generation number for t=t+1. Repeat mutation, recombination and selection operation until a stopping criterion is met, usually a maximum number of iterations (generations), $t_{max}$. The stopping criterion depends on the type of problem.

## 3.3Various Differential (Mutation) Strategies

There are several variations of differential evolution algorithm strategies that can be employed for optimization as mentioned by Sum-Im et al. [2009]. Ten variations, which are defined as the following mutation strategies.

**Differential strategy 1:** In this mutation strategy, the mutant vector can be generated according to the following equation from the randomly chosen base vector

$$V_{ij}^t = P_{R_1j}^t + F\left(P_{R_2j}^t - P_{R_3j}^t\right)(i = 1,2 \dots NG; i \ne d; j = 1,2 \dots L) \text{.............................(3.3)}$$

Where

t is the time (generation)

$p_i^t = [P_{i1}^t, P_{i2}^t, \dots \dots . P_{iNG}^t]^T$ Stands for the position of the i^th individual of a population of real valued NG-dimensional vectors.

$V_i^t = [V_{i1}^t, V_{i2}^t, \dots \dots . V_{iNG}^t]^T$ Stands for the position of the i^th individual of a mutual vector

$R_1$,$R_2$ *and* $R_3$ are mutually different integers that are also different from the running index, i, randomly selected with uniform distribution from the set {1,2,….i-1,i+1,….L}.

F is the mutation factor and F >0 is a real parameter,

**Differential Strategy 2:** In this mutation strategy, the mutant vector can be generated according to the following equation from the best performing vector of the current generation by considering it as base vector

$$V_{ij}^t = P_{Bj}^t + F\left(P_{R_1 j}^t - P_{R_2 j}^t\right)(i = 1,2 \dots NG; i \neq d; j = 1,2 \dots L) \dots\dots\dots\dots\dots\dots\dots\dots..(3.4)$$

where $P_{Bj}^t$ is the best performing vector of the current generation.

**Differential Strategy 3:** In this mutation strategy, the perturbation is applied at a location between the best performing vector and a randomly selected population vector according to the following equation

$$V_{ij}^t = P_{ij}^t + f_B\left(P_{Bj}^t - P_{ij}^t\right) + F(P_{R_1 j}^t\text{-}P_{R_2 j}^t)\ (i = 1,2 \dots NG; i \neq d; j = 1,2 \dots L) \dots\dots\dots(3.5)$$

Where $f_B$ is applied to control the greediness of the scheme, which usually it is set equally to $f_m F$ reduce the number of control variables.

**Differential Strategy 4:** Two difference vectors are used as a perturbation in this mutation strategy.

$$V_{ij}^t = P_{Bj}^t + F\left(P_{R_1 j}^t + P_{R_2 j}^t - P_{R_3 j}^t - P_{R_4 j}^t\right)(i = 1,2 \dots NG; i \neq d; j = 1,2 \dots L) \dots\dots\dots..(3.6)$$

**Differential Strategy 5:** This mutation strategy replaces the best performing vector by a randomly selected vector

$$V_{ij}^t = P_{R_5 j}^t + F\left(P_{R_1 j}^t + P_{R_2 j}^t - P_{R_3 j}^t - P_{R_4 j}^t\right)(i = 1,2 \dots NG; i \neq d; j = 1,2 \dots L) \dots\dots..(3.7)$$

**Differential Strategy 6:** In this mutation strategy, the mutant vector can be generated according to the following equation

$$V_{ij}^t = P_{Bj}^t + F\left(P_{Bj}^t - P_{ij}^t\right)(i = 1,2 \dots NG; i \neq d; j = 1,2 \dots L) \dots\dots\dots\dots\dots\dots\dots\dots\dots.(3.8)$$

**Differential Strategy 7:** The mutant vector can be generated according to the following equation for this mutation strategy

$$V_{ij}^t = P_{Bj}^t + F\left(P_{Bj}^t - P_{ij}^t - P_{R_1 j}^t - P_{R_2 j}^t\right)(i = 1,2 \dots NG; i \neq d; j = 1,2 \dots L) \dots\dots\dots\dots..(3.9)$$

**Differential Strategy 8:** This mutation strategy generates the mutant vector according to the following equation

$$V_{ij}^{t} = P_{Bj}^{t} + f_B\left(P_{Bj}^{t} - P_{ij}^{t}\right) + F(P_{R_1j}^{t}\text{-}P_{R_2j}^{t})\ (i = 1,2 \ldots NG; i \neq d; j = 1,2 \ldots L) \ldots\ldots\ldots(3.10)$$

**Differential Strategy 9:** This mutation strategy generates the mutant vector according to the following equation

$$V_{ij}^{t} = P_{Bj}^{t} + F\left(P_{Bj}^{t} + P_{ij}^{t} - P_{R_1j}^{t} - P_{R_2j}^{t}\right)(i = 1,2 \ldots NG; i \neq d; j = 1,2 \ldots L) \ldots\ldots\ldots\ldots(3.11)$$

**Differential Strategy 10:** This mutation strategy considers the previous generation's best performing vector in order to create the mutant vector

$$V_{ij}^{t} = P_{Bj}^{t} + F\left(P_{Bj}^{t} - P_{Bj}^{t-1}\right)(i = 1,2 \ldots NG; i \neq d; j = 1,2 \ldots L) \ldots\ldots\ldots\ldots(3.12)$$

## 3.4 Advantages

Differential evolution algorithm has a number of significant advantages which are summarized below [40]:

- Differential evolution algorithm has the ability to find the true global minimum regardless of initial parameter values;
- Differential evolution algorithm is fast and simple with regard to application;
- Differential evolution algorithm requires few control parameter;
- Differential evolution algorithm has parallel processing nature and fast convergence;
- DE algorithm is capable of providing multiple solutions in a single run;
- The method is effective on integer, discrete and mixed parameter optimization;
- Differential evolution algorithm has the ability to find the optimal solution for a non-linear constrained optimization problem with penalty functions.

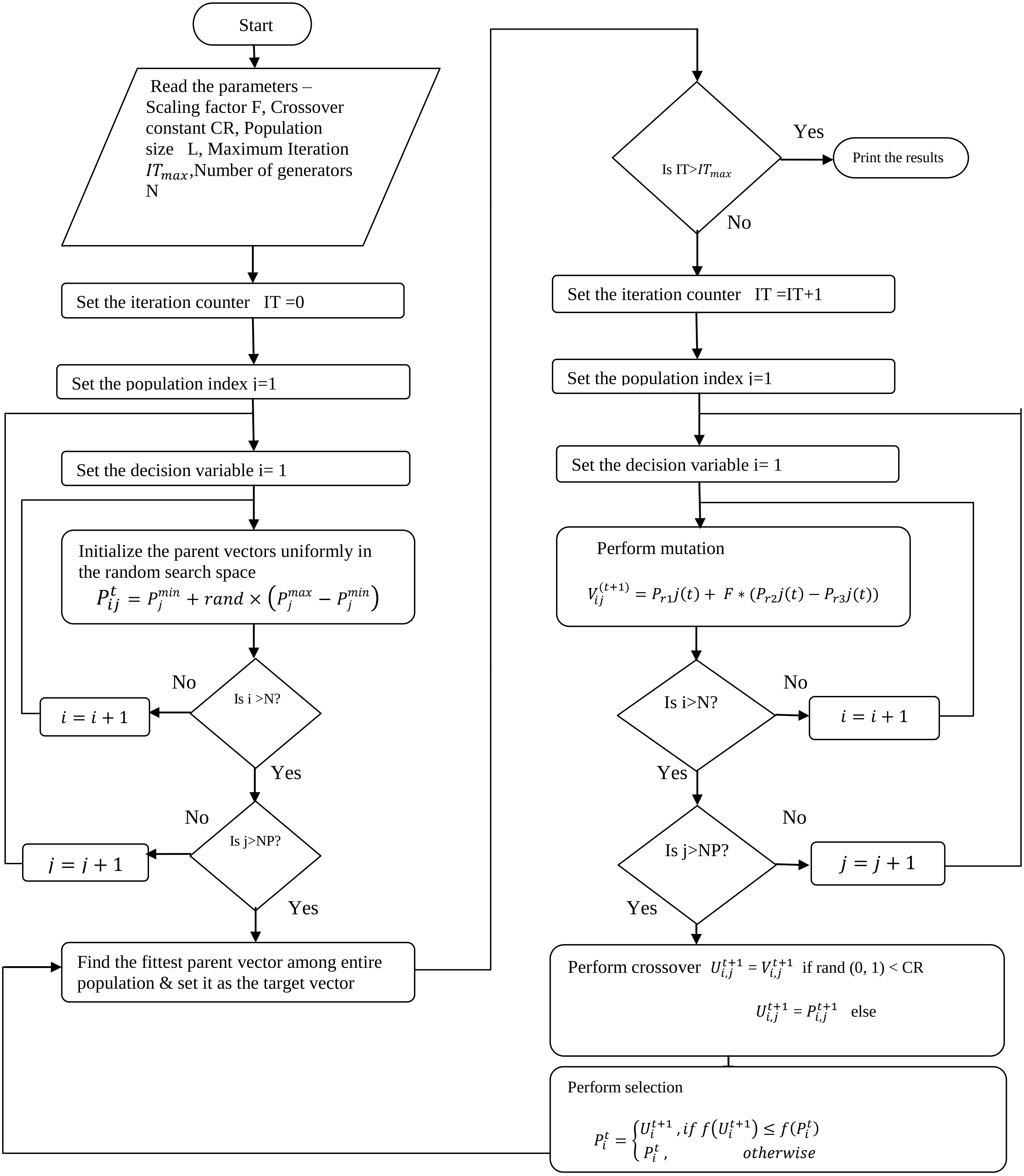
## 3.5 Disadvantages

Although differential evolution algorithm has many advantages explained above, there are also a number of disadvantages of differential evolution algorithm that are summarized below:

- DE algorithm does not always give an exact global optimum due to premature convergence;
- Differential evolution algorithm may require tremendously high-computation time because of a large number of fitness evaluations;
- In differential evolution algorithm, there exist many trials vector generation strategies out of which a few may be suitable for solving a particular problem;

- Moreover, three crucial control parameters involved in differential evolution algorithm, i.e, population size, scaling factor, and crossover rate, may significantly influence the optimization performance.

## 3.6 Flow Chart of DE



# CHAPTER 4

# PROBLEM FORMULATION AND RESULTS

## 4.1Problem Formulation

The OPF problem is solved with variable parameters of TCSC devices. The objective function is minimization of total fuel cost. Therefore the OPF problem in flexible ac transmission system is expressed as follows:

Minimize $\sum_{i=1}^{NG} F_i(P_i)$……………………………………………………………………………(4.1)

$\sum_{i=1}^{NG} F_i(P_i) = \sum_{i=1}^{NG} a_i + b_i P_i + c_i P_i^2 + |d_i * sin\{e_i * (P_i^{min} - P_i)\}|$……………….(4.2)

Subject to

(1) Equality Constraints

$P_{Gi} - P_{Di} - \sum_{j=1}^{NB} V_i V_j \gamma_{ij} \cos(\theta_{ij} + \delta_i - \delta_j) = 0 \quad \forall_i \in N_B$……………………………………….(4.3)

$Q_{Gi} - Q_{Di} - \sum_{j=1}^{NB} V_i V_j \gamma_{ij} \sin(\theta_{ij} + \delta_i - \delta_j) = 0 \quad \forall_i \in N_B$……………………………………..(4.4)

$\sum_{i=1}^{NG} P_{Gi} - P_D - P_L$ =0 …………………………………………………………………………(4.5)

$\sum_{i=1}^{NQ} Q_{Gi} - Q_D - Q_L$ =0…………………………………………………………………………(4.6)

(2) Inequality Constraints

$P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max} \quad \forall_i \in N_G$………………………………………………………………(4.7)

$Q_{Gi}^{min} \leq Q_{Gi} \leq Q_{Gi}^{max} \quad \forall_i \in N_G$………………………………………………………………(4.8)

$V_i^{min} \leq V_i \leq V_i^{max} \quad \forall_i \in N_B$………………………………………………………………(4.9)

$x_{ci}^{min} \leq x_{ci} \leq x_{ci}^{max} \quad \forall_i \in N_{TCSC}$……………………………………………………………(4.10)

## 4.2 Proposed Algorithm: Differential evolution for OPF using TCSC

**Step 1.** Parent vectors of size NP are randomly generated. Elements in a parent vector are real power generation of the generating units excluding slack bus, voltage magnitude and phase angle of the buses excluding slack bus and series capacitors of TCSC. The i$^{th}$ parent vector is as follows:

$p_i = [P_{G1}^i$………..$P_{Gm}^i \dots\dots P_{GNg}^i, V_1^i \dots\dots.. V_m^i \dots\dots. V_{Nb}^i, .. \delta_1^i \dots\dots\dots. \delta_m^i \dots\dots\dots. \delta_{Nb}^i,$

$x_{c1}^i$………$x_{cm}^i \dots\dots. x_{cNTCSC}^i \;]^T$. Newton–Raphson load flow is run for each parent vector p$_i$.

The reactive power generations, transmission loss, slack bus generations and line flows are calculated. Cost of generation is calculated for each parent vector $p_i$.

**Step 2.** Perform mutation for each target vector as described in Section 3.2.2

**Step 3.** Perform crossover for each target vector and create a trial vector as mentioned in Section 3.2.3

**Step 4**. Perform selection for each target vector, by comparing its cost with that of the trial vector. The vector that has lesser cost of the two would survive for the next generation.

**Step 5**. Stop if the maximum number of generations is reached otherwise go to Step 2.

Table 4.1 Line Data for IEEE 14 Bus system

| From Bus | To Bus | R pu | X pu | B/2 pu | X'mer Tap Ratio |
|---|---|---|---|---|---|
| 1 | 2 | 0.01938 | 0.05917 | 0.0264 | 1 |
| 1 | 8 | 0.05403 | 0.22304 | 0.0246 | 1 |
| 2 | 3 | 0.04699 | 0.19797 | 0.0219 | 1 |
| 2 | 6 | 0.05811 | 0.17632 | 0.0170 | 1 |
| 2 | 8 | 0.05695 | 0.17388 | 0.0173 | 1 |
| 3 | 6 | 0.06701 | 0.17103 | 0.0064 | 1 |
| 6 | 8 | 0.01335 | 0.04211 | 0.0 | 1 |
| 6 | 7 | 0.0 | 0.20912 | 0.0 | 0.978 |
| 6 | 9 | 0.0 | 0.55618 | 0.0 | 0.969 |
| 8 | 4 | 0.0 | 0.25202 | 0.0 | 0.932 |
| 4 | 11 | 0.09498 | 0.19890 | 0.0 | 1 |
| 4 | 12 | 0.12291 | 0.25581 | 0.0 | 1 |
| 4 | 13 | 0.06615 | 0.13027 | 0.0 | 1 |
| 7 | 5 | 0.0 | 0.17615 | 0.0 | 1 |
| 7 | 9 | 0.0 | 0.11001 | 0.0 | 1 |
| 9 | 10 | 0.03181 | 0.08450 | 0.0 | 1 |
| 9 | 14 | 0.12711 | 0.27038 | 0.0 | 1 |
| 10 | 11 | 0.08205 | 0.19207 | 0.0 | 1 |
| 12 | 13 | 0.22092 | 0.19988 | 0.0 | 1 |
| 13 | 14 | 0.17093 | .34802 | 0.0 | 1 |

Table 4.2 Bus Data for IEEE 14 Bus system

| Bus | Type | Vsp | Theta | PGi | QGi | PLi | QLi | Qmin | Qmax |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1.060 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 2 | 1.045 | 0 | 0.40 | 0.424 | 0.217 | 0.127 | -0.40 | 0.50 |
| 3 | 2 | 1.010 | 0 | 0 | 0.234 | 0.942 | 0.190 | 0 | 0.40 |
| 4 | 2 | 1.070 | 0 | 0 | 0.122 | 0.112 | 0.075 | -0.06 | 0.24 |
| 5 | 2 | 1.090 | 0 | 0 | 0.174 | 0.0 | 0.0 | -0.06 | 0.24 |
| 6 | 3 | 1.0 | 0 | 0 | 0 | 0.478 | -0.039 | 0 | 0 |
| 7 | 3 | 1.0 | 0 | 0 | 0 | 0.0 | 0.0 | 0 | 0 |
| 8 | 3 | 1.0 | 0 | 0 | 0 | 0.076 | 0.016 | 0 | 0 |
| 9 | 3 | 1.0 | 0 | 0 | 0 | 0.295 | 0.166 | 0 | 0 |
| 10 | 3 | 1.0 | 0 | 0 | 0 | 0.090 | 0.058 | 0 | 0 |
| 11 | 3 | 1.0 | 0 | 0 | 0 | 0.035 | 0.018 | 0 | 0 |
| 12 | 3 | 1.0 | 0 | 0 | 0 | 0.061 | 0.016 | 0 | 0 |
| 13 | 3 | 1.0 | 0 | 0 | 0 | 0.135 | 0.058 | 0 | 0 |
| 14 | 3 | 1.0 | 0 | 0 | 0 | 0.149 | 0.050 | 0 | 0 |

Table 4.3 Generator Data for IEEE 14 Bus system

| Bus no. | $P_G^{min}$(MW) | $P_G^{Max}$(MW) | a($/h) | b($/MWh) | c($/MW$^2$h) | d($/h) | e(rad/MW) |
|---|---|---|---|---|---|---|---|
| 1 | 50 | 250 | 0 | 2.00 | 0.0037 | 18.00 | 0.0370 |
| 2 | 20 | 80 | 0 | 1.4500 | 0.0175 | 16.00 | 0.0380 |
| 3 | 15 | 50 | 0 | 1.0000 | 0.0625 | 14.00 | 0.0400 |
| 4 | 10 | 35 | 0 | 3.2500 | 0.0083 | 12.00 | 0.0450 |
| 5 | 10 | 30 | 0 | 3.0000 | 0.0250 | 13.00 | 0.0420 |

## 4.3 Results

The IEEE 14-bus system has been used to show the effectiveness of the proposed algorithm. The data used was given in Table 4.1, 4.2 and 4.3. In this work, two branches, (2, 3), (6, 8) are installed with TCSC. Voltage magnitude limits of generator buses are set to 0.95 p.u. ≤ V ≤ 1.1 p.u. and load buses are set to 0.95 p.u. ≤ V ≤ 1.05 p.u. Voltage angle limits are taken as $-14° < \delta < 0°$ . Limits of the series capacitors limits are taken in such a manner that the ratio of maximum series capacitors limit to line reactor is equal or more than 50%. The values of mutation factor and crossover rate are considered as 0.5 and 0.88. The population size is 20. The DE reduces the cost significantly when used with TCSC and are reported in table 4.4.

Table 4.4 Power Generations, Cost and Losses Comparison

| **Generators** | **Power Generation with TCSC using DE** | **Power Generation without TCSC using DE** | **Power Generation Using Conventional Load flow method** |
|---|---|---|---|
| G1(MW) | 162.81 | 162.30 | 232.60 |
| G2(MW) | 34.95 | 61.03 | 40 |
| G3(MW) | 26.10 | 21.56 | 0 |
| G4(MW) | 20.81 | 13.82 | 0 |
| G5(MW) | 22.58 | 10.00 | 0 |
| **Cost($/h)** | **746.2312** | **754.7656** | **801.0287** |
| **Losses(MW)** | **8.2542** | **9.711** | **13.600** |

Table 4.5 Bus Voltages and Angles obtained from conventional load flow method

| **Bus No.** | **Voltages (pu)** | **Angle Degree** |
|---|---|---|
| 1 | 1.0000 | 0 |
| 2 | 1.0450 | -4.9957 |
| 3 | 1.0200 | -12.8726 |
| 4 | 1.0600 | -14.4096 |
| 5 | 1.0800 | -13.2742 |
| 6 | 1.0139 | -10.2425 |
| 7 | 1.0444 | -13.2742 |
| 8 | 1.0159 | -8.7337 |
| 9 | 1.0274 | -14.8829 |
| 10 | 1.0255 | -15.0875 |
| 11 | 1.0390 | -14.8713 |
| 12 | 1.0436 | -15.2771 |
| 13 | 1.0375 | -15.3247 |
| 14 | 1.0134 | -16.1166 |

Table 4.6 Bus Voltages and Angles obtained from DE without using TCSC

| Bus No. | Voltages (pu) | Angle Degree |
|---|---|---|
| 1 | 1.0000 | 0 |
| 2 | 1.0026 | -3.9821 |
| 3 | 0.9981 | -11.0747 |
| 4 | 0.9829 | -12.0017 |
| 5 | 0.9700 | -9.8988 |
| 6 | 0.9643 | -8.6329 |
| 7 | 0.9636 | -10.9786 |
| 8 | 0.9649 | -7.2713 |
| 9 | 0.9500 | -12.9502 |
| 10 | 0.9500 | -13.1204 |
| 11 | 0.9606 | -12.7057 |
| 12 | 0.9653 | -13.0401 |
| 13 | 0.9586 | -13.1256 |
| 14 | 0.9500 | -14.2504 |

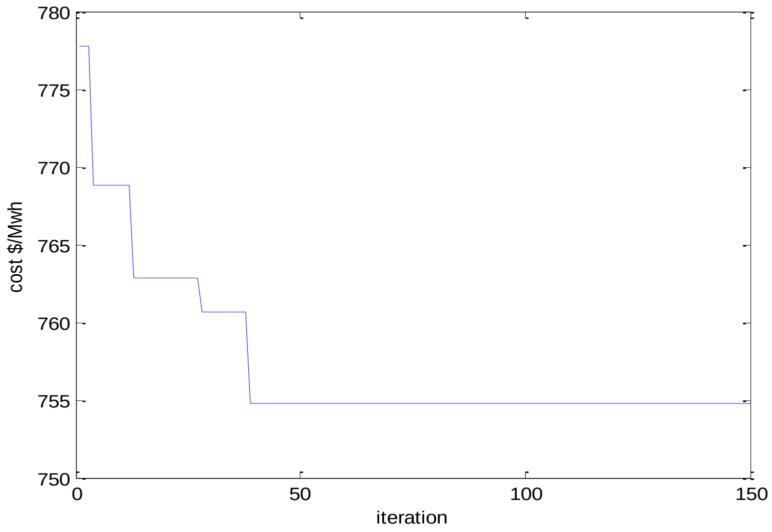


Figure 4.1 Cost curve using DE without TCSC

Table 4.7 Bus Voltages and Angles obtained from DE with using TCSC

| Bus No. | Voltages (pu) | Angle Degree |
|---|---|---|
| 1 | 1.0000 | 0 |

|  |  |  |
|---|---|---|
| 2 | 0.9874 | -3.9624 |
| 3 | 0.9876 | -8.8393 |
| 4 | 1.0249 | -10.1571 |
| 5 | 1.0343 | -6.5195 |
| 6 | 0.9727 | -7.5957 |
| 7 | 1.0011 | -8.7206 |
| 8 | 0.9742 | -6.6609 |
| 9 | 0.9850 | -10.7615 |
| 10 | 0.9841 | -10.9635 |
| 11 | 1.0005 | -10.6886 |
| 12 | 1.0075 | -11.0981 |
| 13 | 1.0006 | -11.1509 |
| 14 | 0.9726 | -12.0589 |

Table 4.8 Values of TCSC element obtained from DE

|  |  |
|---|---|
| $x_{c2-3}$ | 0.0826 |
| $x_{c6-8}$ | 0.0090 |

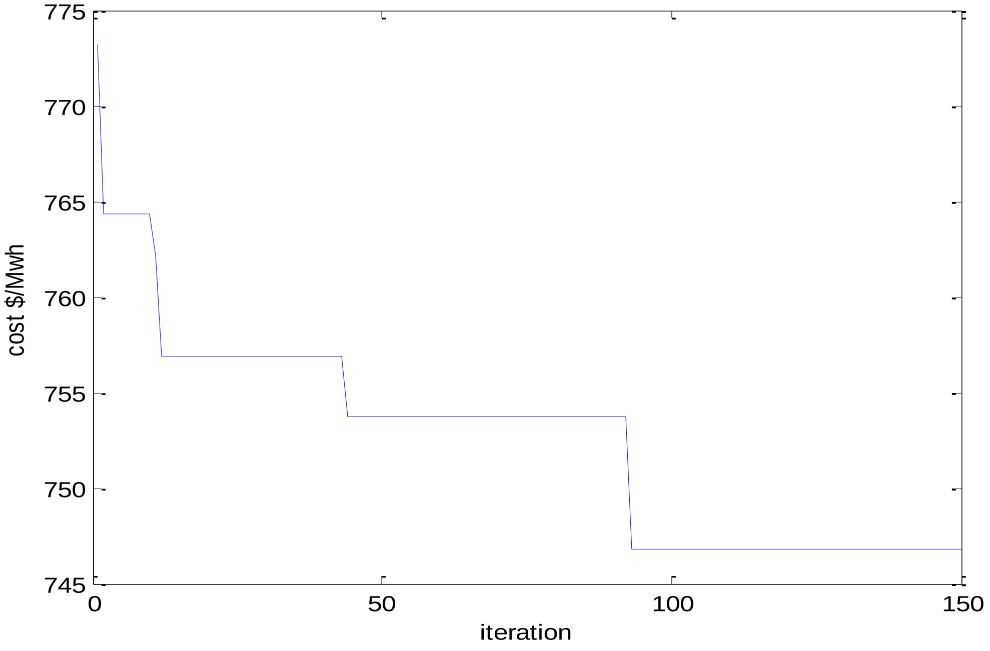


Figure 4.2 Cost Reduction using DE with TCSC

# CHAPTER 5

# CONCLUSIONS AND FUTURE SCOPE

## 5.1 Conclusions

Differential Evolution is simple but powerful stochastic algorithm. In this dissertation, differential evolution is successfully implemented to minimize the generator fuel cost in optimal power flow control with TCSC devices keeping the equality and inequality constraints in limits. Differential evolution achieves better solution and requires less CPU time on modified IEEE 14-bus system with TCSC fixed at the given locations with respect to conventional load flow methods.

## 5.2 Future Scope

1. Optimal power flow control can be improved using hybrid FACTS devices.
2. DE variants can be explored to solve the optimisation problem.

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