Chapter – 1

INTRODUCTION

1.0 The Importance of Reactive Power:

Control of active and reactive power flows in order to have maximum possible economy and satisfactory level of security is the main function of an electric power system. Active power, being the working component of ac power, gets more attention. It earns revenue, maintains system frequency and integration of power system. Reactive power, on the other hand, is the supporting power. It maintains system voltage and allows active power to flow through the system components. The wattless component of electrical power, popularly referred to as VAR, thus plays a very important role in the operation of power system. Loads in ac power systems, almost invariably, are of lagging power factors, thus requiring reactive powers to be supplied from the synchronous generators. As the generators deliver the wattless component of power, they simultaneously become a weaker source for delivering the active power. This reduction in capacity can be determined from the operating chart of the synchronous generators. Though the resulting losses in revenues on the generator side may be compensated for by management decisions, the losses incurred to the power system are incompensable as the flow of reactive power from the generators through the transformers and transmission lines cause large voltage drops and heating losses. Local generation of reactive powers have therefore been attempted since the early days of power system operation.

As the interconnection in power system increased, the necessity to transfer bulk power over longer distances were felt. The growth in load, however, was not matched by a corresponding growth in transmission capacity. Moreover, with the availability of efficient control devices, there had been increased tendency to load the transmission lines more close to their stability limits. This has given rise to the so called problem of voltage stability whereby the collapse of bus voltages have been observed. Voltage stability problem has assumed increased importance after the occurrences of a number of
blackouts and the lack of sufficient reactive power supply has been identified as the main reason behind those voltage collapses.

Reactive power thus, is not just an economic issue. More importantly, it is a key to the security of the power systems.

1.1 Sources of Reactive Power:

Synchronous generators, equipped with automatic voltage regulators, are the most convenient source of reactive power though they are not the most desirable ones. But Synchronous Generators can provide very fast and hazard free control of reactive power. Thus, they are preferred to be the reserve sources to be used for emergency control.

Traditionally, tap changing transformers and shunt capacitors were used for control of voltage and reactive power in power systems. For tap changing transformers voltage control is a secondary function as they are primarily being used as power transformers, tap changing facility being used as an additional feature.

Unlike the tap changers, shunt capacitors are meant for supplying the reactive power only and they are located at voltage critical buses of the power system. Shunt capacitors are used either as fixed or switched devices. In case of fixed capacitors reactive power output is fixed irrespective of the system requirements. Switched capacitors, on the other hand, are switched on and off as the system demand changes. Though switched capacitors are more desirable control devices than the fixed capacitors, they generally involve more costs as well as more operational hazards.

Both the transformer and shunt capacitors are step control devices. With the advent of power electronics and FACTS, a new class of reactive power control devices are now available in the name of Static Var Compensators (SVC), Static Condensers (STATCOM) etc. These devices are capable of performing step less control of reactive power. They however are associated with the problem of injecting harmonics into the system and at the same time are too costly. So bulk share of the function of reactive power control are still lying with the shunt capacitors, tap changers and the synchronous generators.
1.2 The Problem of Reactive Power:

It is well known that the best possible way of solving the reactive power problems is to generate the reactive power at the point of its demand. But the restrictions come from the economy and the limitations in the available capacity of such resources. Practical considerations allow reactive power sources to be installed at a limited number of locations only. The problem, therefore, is to identify the best locations from a number of candidate locations. And once the locations are identified, the question to be answered is how much reactive power has to be generated from an identified location. The first problem is that of placement of Var sources and the second one is the sizing of Var sources. Though identified separately, these problems are interdependent and have to be solved simultaneously. The well known $\frac{2}{3}$rd rule for the placement of Var source in simple radial feeders becomes ineffective even for large distribution systems as well as interconnected networks and effective solution of the problem requires optimization techniques to be applied. The problem of placing and sizing of Var sources is basically a planning problem and has to be determined considering the cost of Var sources, available loads and the cost of energy generation.

Reactive power problem has also to be solved in a different context when Var sources are already installed. As the loads on the system vary throughout the day, operations of the existing Var sources are to be coordinated so as to have the best possible system condition in respect of the energy loss and the node voltage profile. This is the so called problem of reactive power dispatch. The problem is somewhat less involved compared to the planning problem as it need not consider the investment costs associated with the Var sources. But the solution of this problem too requires the application of rigorous mathematical programming techniques.

1.3 Cost of Reactive Sources:

Of the various reactive power sources capacitors are the most commonly used one. Capacitors have two cost components; a fixed installment cost irrespective of the size of the capacitor and a purchase cost dependent upon the MVA capacity. In practice,
Conventional formulation of the reactive power planning problem does not include the cost of generators or tap changers as their primary functions are different. Reactive power dispatch problem does not even include the cost of capacitors as the problem here is to minimize the power loss only using the existing reactive power sources. More recently with the adoption of the concept of deregulation increased attentions is being paid to the reactive power issues. Pricing of reactive power has become a necessity for successful implementation of competition in power industry. This has lead to the problem of ‘reactive power valuation’ whereby depending upon the investment costs of the generator or transformer a value is assessed for the reactive power supplied. This assessed value of the reactive power may then be used as a guideline for the pricing of reactive power.

1.4 Problem Formulation:

The objective of the reactive power dispatch problem is to minimize the transmission losses utilizing the available Var sources in the system. Mathematically, the problem may be expressed as minimizing the power loss

\[ P_{\text{loss}} = \sum_{i} \left( V_i^2 + V_j^2 - 2V_i V_j \cos \theta \right) \]

Subject to the nodal active and reactive power balance

\[ P(v, \delta) = 0 \]
\[ Q(v, \delta) = 0 \]
Power limit constraints

\[ P_{\text{min}} \leq P_n \leq P_{\text{max}} \]

\[ Q_{\text{min}} \leq Q_n \leq Q_{\text{max}} \]

Voltage magnitude constraints: \( V_{\text{min}} \leq V_i \leq V_{\text{max}} \)

OLTC tap constraints \( t_{\text{min}} \leq t_k \leq t_{\text{max}} \)

And the existing nodal reactive capacity constraints: \( Q_{\text{min}} \leq Q_i \leq Q_{\text{max}} \)

The planning problem solves an enlarged set of equations including the investment costs of the components. The objective function to be minimized is:

\[
CP = \sum_{i,j} \left( O_{o1} C_{n} + C_{o1} \right) + \sum_{i} \left( V_i^2 + V_j^2 - 2V_i V_j \cos \theta_{ij} \right)
\]

The constraint set consists of those mentioned above for the dispatch problem plus the additional constraint due to the new Var sources \( Q_{\text{min}} \leq Q_i \leq Q_{\text{max}} \)

In the above:

- \( L \) = total number of lines in the system.
- \( i,j \) = end buses of line \( k \).
- \( g_{ij} \) = conductance of branch \( i-j \).
- \( \theta_{ij} \) = phase angle difference between buses \( i \) & \( j \).
- \( G_{ij} \) = real part of the mutual admittance between bus \( i \) & \( j \).
- \( B_{ij} \) = imaginary part of the mutual admittance between bus \( i \) & \( j \).
- \( t_k \) = tap setting of the \( k \)th transformer.
- \( P_{gi} \) = Active power generation at bus \( i \).
- \( P_{di} \) = Active power demand at bus \( i \).
- \( Q_{gi} \) = Reactive Power generation at bus \( i \).
- \( Q_{di} \) = Reactive Power demand at bus \( i \).
- \( Ce \) = cost of energy loss.
\[ C_n = \text{cost per Kvar of new reactive source.} \]
\[ N = \text{Number of locations of new Var sources.} \]

In general terms the optimum reactive power problem can be expressed mathematically as

\[
\begin{align*}
\text{minimize} & \quad f(x, u) \\
\text{subject to equality constraint} & \quad g(x, u) = 0 \\
\text{and inequality constraint} & \quad h(x, u) \leq 0
\end{align*}
\]

and upper and lower limits of the controlled variables \( x \) and control variables \( u \),

\[
\begin{align*}
x_i^{\text{min}} & \leq x_i \leq x_i^{\text{max}}; \\
u_i^{\text{min}} & \leq u_i \leq u_i^{\text{max}}
\end{align*}
\]

For the reactive power planning problem the objective function, conventionally, is to minimize the cost of new investment in capacitor/reactor banks along with the cost of power losses.

In case of the reactive power dispatch problem the objective functions consists of the minimization of the energy losses only.

Security constrained reactive dispatch problem however formulates the objective function as a performance index that gives a measure of the system security under specified contingency conditions. Such objective functions may be formulated to maximize the reactive reserves of the synchronous generators or to minimize the sum of the squares of deviations from an optimal operating point,

\[
Z^* = \left( u^*, x^* \right), \text{ written as } F(Z) = \sum_k \sum_i \left( Z_i^k - Z_i^* \right)^2
\]

where, \( k = 1,2, \ldots, n_c \), \( n_c \), being the number of contingency cases.

Equality constraint \( g(x, u) = 0 \), represents the nodal active and reactive power balances given by

\[
\begin{align*}
P_i^{\text{sp}} - P_i(v, \delta) &= 0 \\
Q_i^{\text{sp}} - Q_i(v, \delta) &= 0, \quad i = 1, \ldots, n
\end{align*}
\]
Inequality constraint, most commonly, represents the reactive capacity limits of the synchronous generators and the synchronous condensers given by

$$Q_{G_i}^{\text{min}} \leq Q_{G_i} \leq Q_{G_i}^{\text{max}}, \quad i = 1, \ldots, n$$

Control variable $u$, consists of the generator reactive power outputs $Q_g$, capacitor reactive power $Q_c$, tap changer setting $t$ and the selected bus voltages.

Controlled variable $x$, on the other hand consists of the load flow variables $v$ and $\delta$.

It may be noted that the generator and the capacitor reactive power may appear either in the control or the controlled variable lists depending upon the formulation, application and requirements.

1.5 Solution of the Reactive Power Problem:

Though the problem of reactive power optimization is non linear in nature both the linear and non linear optimization techniques have extensively been used for its solution. Because of the stepped variation of the procurement cost of the reactive sources, the objective function always needs some form of linearization when classical optimization techniques are used. The equality constraints and the functional inequality constraints basically comprise of the power flow equations. Thus, in most of the cases, they are most conveniently handled through the jacobian of the Newton-Raphson load flow. Successive linearization of the power flow equations thus forms the basis of the application of the classical optimization techniques for solving the active and reactive power optimization problems.

A linear programming formulation reduces to a form

minimize:
\[ f = (k_1[L] + [H : 0 : 0]) \begin{bmatrix} \Delta Q_c \\ \Delta V_g \\ \Delta T \end{bmatrix} \]

Subject to

\[
\begin{bmatrix}
\Delta V_{L}^{\text{min}} \\
\Delta Q_{g}^{\text{min}} \\
\Delta Q_{c}^{\text{min}} \\
\Delta V_{g}^{\text{min}} \\
\Delta T^{\text{min}}
\end{bmatrix} \leq \begin{bmatrix} S \\ 1 \\ 1 \\ 1 \end{bmatrix} \begin{bmatrix}
\Delta Q_c \\
\Delta V_g \\
\Delta T
\end{bmatrix} \leq \begin{bmatrix} \Delta V_{L}^{\text{max}} \\
\Delta Q_{g}^{\text{max}} \\
\Delta Q_{c}^{\text{max}} \\
\Delta V_{g}^{\text{max}} \\
\Delta T^{\text{max}}
\end{bmatrix}
\]

where, \( L \) and \( S \) are the sensitivity sub matrices obtained from power flow jacobian, \( H \) indicates unit cost vector relating to the capacitive var sources and \( k_1 \) is a factor converting MW system loss to annual expenses.

Non-linear programming formulation minimizes the Lagrange function

\[ L(u, x, \lambda) = f(x,u) - \lambda^T g(x,u). \]

when Newton’s method is applied, the optimality condition reduces to

\[
\begin{bmatrix} A \\
\Delta x \\
\Delta \lambda 
\end{bmatrix} = - \begin{bmatrix} \frac{\partial L}{\partial U} \\
\frac{\partial L}{\partial x} \\
\frac{\partial L}{\partial \lambda} 
\end{bmatrix}
\]

Elements of \( A \) are the second order partial derivatives of the Lagrangian, which also include the jacobian of the Newton-Raphson load flow.

A Quadratic programming formulation of the problem represents the objective function as

\[ \min_x \left\{ f(x) = c^T x + \frac{1}{2} x' C x \right\} \]
Subject to,

\[ x^{\text{min}} \leq x \leq x^{\text{max}}, \quad y^{\text{min}} \leq y \leq y^{\text{max}} \]

Subject to \( y = Sx \)

Where, \( f(x) \) is a quadratic approximation of the objective function used in the general non linear optimal reactive power flow problem;

\[ x = \text{col} \left[ \Delta V, \Delta Q, \Delta t \right] \]

\[ c' = \text{row} \left[ \frac{\partial P_L}{\partial V_i}, \frac{\partial P_L}{\partial Q_i}, \frac{\partial P_L}{\partial t_i} \right] \]

and

\[ C = \begin{bmatrix}
\frac{\partial^3 P_L}{\partial V_i \partial V_i \partial V_i} & \frac{\partial^3 P_L}{\partial V_i \partial Q_i \partial V_i} & \frac{\partial^3 P_L}{\partial V_i \partial t_i \partial V_i} \\
\frac{\partial^3 P_L}{\partial V_i \partial V_i \partial Q_i} & \frac{\partial^3 P_L}{\partial V_i \partial Q_i \partial Q_i} & \frac{\partial^3 P_L}{\partial V_i \partial t_i \partial Q_i} \\
\frac{\partial^3 P_L}{\partial V_i \partial V_i \partial t_i} & \frac{\partial^3 P_L}{\partial V_i \partial Q_i \partial t_i} & \frac{\partial^3 P_L}{\partial V_i \partial t_i \partial t_i} \\
\frac{\partial^3 P_L}{\partial t_i \partial V_i \partial V_i} & \frac{\partial^3 P_L}{\partial t_i \partial Q_i \partial V_i} & \frac{\partial^3 P_L}{\partial t_i \partial t_i \partial V_i}
\end{bmatrix} \]

\( V \)'s are the generator voltages, \( Q \)'s are reactive power injectors, \( t \)'s are transformer turns ratios and \( S \) is the sensitivity matrix.

Compared to these classical methods of optimization, the Interior point method is a more recent development. This method has also been used to solve the reactive power optimization problem.

### 1.6 A Brief Review of the Existing Solution Techniques:

A brief outline of sum of the published works on the reactive power optimization problem is given below.

In [1, 1988] optimal power system planning and operation is expressed as a multi objective optimization problem. E – constrained technique is used to obtain a set of non
inferiority solutions. Idea of preference index is introduced to decide the optimal solution. Security index is chosen as the preference index.

In [2, 1988] the authors have presented a method for Reactive Power Planning using linear programming. Utilizing this method authors have found optimal solution for both allocation and operation planning in large systems. The objective function was chosen as to minimize the real power loss during operation and/or control. For investment planning, objective function was considered in such a way so that it can also minimize the installation cost of new capacitor/reactor.

In [3, 1988] the authors have claimed for an accurate and fast technique for real time control of system voltage and reactive power of large-scale power systems. They have divided the original system into many subsystems and tried to obtain an optimum solution for each subsystem. The selection of various subsystems is based on the closeness of the VAR control variable and on the voltage sensitivity criterion using impedance matrix of the system. The final optimum solution for the overall system is obtained by co-ordination of subsystem solutions.

In [4, 1989] a method was presented for identifying weak areas of a system that prevent convergence of the Newton–Raphson method. This method gives idea to the power system operator for identification of weak nodes of the system. This information is very much useful to pin-point the area where system modification or data corrections are to be made immediately.

In [5, 1989], the reactive power dispatch is formulated by minimizing real power loss utilizing all the control variables, such as transformer, generator var sources and switch-able shunt capacitors. The solution of the loss problem is obtained by successively solving quadratic problems. First and second order loss sensitivity coefficients were derived for the quadratic problem formulation.

In [6, 1990], Dual simplex linear programming technique is employed for power system VAR planning. The major differences between this paper and the previous papers, as claimed by the author are

1. The number of load flow cases has been minimized.
2. Network changes are analyzed via contingency analysis.
In [7, 1990] General Capacitor Placement problem in a distribution system is described. How simulated annealing technique can be applied for the solution of the above mentioned problem is described. The problem was described as a combinatorial optimization problem with a non-differentiable objective function.

In [8, 1990] solution algorithm for the previous work [7, 1990] and the test results are shown under different loading conditions.

In [9, 1990] the large power system is decomposed into sub areas and main objective was to minimize the real power loss for optimal economic dispatch. Here also the objective function was linearized in order to use LP. The main problem is divided into several sub problems corresponding to each sub area and each sub problem is solved for optimal solution.

In [10, 1990] Newton's optimal power flow is applied for the solution of the secondary voltage / reactive power control in a transmission network. Here, decentralized secondary voltage / VAR control is dealt. The determination of the control zone is based on the aggregation of strongly coupled zones into homogeneous groups in regard to the voltage / VAR performance. Determination of zones pilot nodes are guided by the sensitivity matrix whose elements are the sensitivity coefficients of node voltages for changes in VARs injected at load nodes, assuming the availability of the primary voltage / VAR control only. Here, in this paper, the location and role of all control resources and regulating devices, participating in system's voltage / VAR control is defined.

A decomposition co-ordination scheme of control variables are presented in [11, 1991] by decomposing the main problem in to sub problems and also contingency analysis and screening is performed. The set of control variables are partitioned in such a way that the most effective subset of controls is associated with each of the all contingencies. Each contingency forms a sub optimization problem. The results of the optimization of each of the contingencies are then treated for the adjustment of the control variables of the intact system.

In [12, 1991] two rule based techniques which predict the impact of voltage control devices on power system bus voltages are presented using a "reactive path concept". By first technique, in each control region voltage control device is allocated. In
the second technique only two controllers are assigned to a given bus for best control settings among all controllers.

In [13, 1991] a two level decomposition approach for VAR sources planning in electric power systems is described. Here the proposed method uses Benders decomposition technique with some significant differences. Here Q/V operation sub problem is solved for each one of the base cases and the contingencies (either under preventive or corrective) being considered.

In [14, 1992] Linear programming approaches have been proposed for the steady state control problem. In this paper, multiple objectives and soft constraints are modeled using fuzzy sets. Piece-wise linear convex membership functions for the fuzzy sets are defined. Discrete constraints are also considered.

In [15, 1992] knowledge and algorithm based approach to VAR planning in a transmission system is presented. Two expert system modules, SACS (System analysis and curve selection) and VPES (Var planning expert system) are proposed for solving the Var planning problem considering both contingencies and voltage collapse. SACS analyzes the operating condition and this selects the P – V / Q – V / S – V curves for the voltage collapse study. VPES determines the size and locations of the new compensator installation.

In [17, 1992] modal analysis approach has been discussed. It involves the computation of a small number of eigen values and the associated eigen vectors of a reduced Jacobian matrix. The eigen values of the reduced Jacobian identify different modes through which the system could become voltage unstable. The magnitude of the eigen values provides a relative measure of proximity to instability.

In [18, 1993] a flexible approach based on approximation to a coordinated control of voltage and reactive power is presented. Voltage reactive power control problem is modeled by fuzzy sets and a prototype of voltage reactive power controller is developed and finally this prototype was applied to a several test cases in a model system.

In [19, 1993], a tool for planning the installation of reactive power sources is presented. Since load demand is uncertain, stochastic approach has been adopted. The tool is based on the capability chart of the power system that describes the domain of allowable operation of the system in the plane of total active and reactive load demand.
In [20, 1993] a fuzzy based LP approach to the optimal control of reactive power is presented. The objective function and the constraints are modeled by fuzzy sets. The fuzzy sets are used to formulate the problem in such a way that objective is to minimize the real power losses and also maintaining the voltages within crisp limits and prevent an infeasible solution by allowing critical voltages to exceed their limits with a smaller degree of satisfaction. The overall solution was defined as the intersection of the fuzzy constraints and objectives.

In [21, 1993] Interior point method (IPM) is described for the solution of linear programming problems and how this method is far more superior to simplex method is also explained by solving security constrained economic dispatch problem on IEEE systems.

In [22, 1994] Interior point method based on the Primal – Dual algorithm for the optimal reactive dispatch problem is presented.

In [24, 1994] Genetic Algorithm is used for optimal reactive power planning. The principal features of their proposed methods are of

1. Searching of multiple paths to reach a global optimal.
2. Uses various objective functions simultaneously
3. Treats integer / discrete variables.

In [25, 1994] K.H. Abdul Rahaman and S.M. Shahidepour presents a solution to the optimal voltage / reactive power control problem taking into account the uncertainty associated with the reactive power demand. Since reactive power demand is uncertain, the objective of minimizing real power loss under different loading conditions are treated by fuzzy modeling of loads.

In [26, 1994] V. Ajjarapu, Ping Lin Lau, S. Battula introduces a method of determining the minimum amount of shunt reactive power that indirectly maximizes the real power transfer before voltage collapse is encountered. To achieve an economical solution at a given load level, the proposed method was formulated as a non-linear constrained optimization problem called predictor corrector optimization scheme that minimizes the amount of shunt reactive power injection. This paper recognizes the
sensitivity information derived from continuation power flow as a reliable source for identifying weak buses that are prone to voltage collapse.

In [27, 1995] Artificial Intelligence (AI) approach for optimal reactive power control problem incorporates the reactive load uncertainty in optimizing the overall system performance. The artificial neural network (ANN) enhanced by fuzzy sets is used to determine the membership of control variables corresponding to the given load values. ANN is trained to identify the closest solution for a given load input. Then an expert system is used to adjust control variables and achieve an economical and practical solution.

In [28, 1995] authors have proposed a post processing procedure of economic dispatch solutions based on conventional economic dispatch and the approximate reasoning for improved security. At first authors have solved dynamic dispatch problem. Then branch power flow and their sensitivity to real power control are calculated from the load flow solutions using the original economic dispatch output. Then the loading rates of branch flow are evaluated and the supplementary corrective actions are determined to reduce the branch flows for potential contingencies.

Reactive power planning along with reactive power pricing problem is analyzed in [32, 1996]. A simple bus wise cost benefit analysis (CBA) scheme is proposed which involves solving a modified optimal power flow problem (OPF) iteratively. This technique obviates the need to introduce integer variables. A bus wise two part tariff scheme for reactive power has been proposed comprising a fixed part component which recovers the investment costs incurred and a real time part to reflect the operating costs incurred by the utility while supplying the residual reactive power requirement.

In [33, 1996] authors have suggested energy storage devices incorporating microprocessor and power electronics, coupled through a communication network can provide an opportunity to enhance existing control measures for inter connected power system.

In [34, 1996], authors have proposed a heuristic method for the solution of reactive power planning problems. A binary search technique is used to find a possible solution with the discrete nature of reactive sources.
In [38, 1996], Soumen Ghosh and Badrul H. Chowdhury proposed a method based on transformation of the energy function minimization problem into a set of ordinary differential equation. They have introduced a new LP based security – constrained rescheduling algorithm first and then discuss the customization of the Hopfield neural network for constrained optimization.

In [39, 1996] weak bus oriented reactive power planning for system security is presented. The algorithm identifies weak buses and selects those buses as candidate buses for installing new reactive power sources to enhance system security. Simulated annealing is applied to obtain the global optimal solution of the constrained, non-differentiable optimization problem.

The proposed approach in [41, 1997] consists of Newton's method applied to a search of the stationary necessary conditions of the Augmented Lagrangian function. The difficulty to identify the binding inequality constraints set is removed by the introduction of dual variables and quadratic penalty terms enclosed in the Augmented Lagrangian function.

In [47, 1998] successive quadratic programming method is presented for reactive power optimization. The method is based on the search of the best of the optimal point between two solutions on sequential approximating programming procedure and considers as change of objective function on this interval and violation of inequality constraints.

A cost based reactive power dispatch is presented in [50, 1999]. In this paper, the explicit and implicit costs of reactive support from generation and transmission sources are analyzed. The concept of opportunity cost is proposed. This opportunity cost is a function of the cost and market price of real power. Minimization of total cost was the new objective of reactive power dispatch.

In [52, 2000] a method for reactive power planning against voltage collapse is presented. Modal analysis is used to generate a participation factor based voltage collapse sensitive index (VCSI). VCSI is used to rank and select the site of new capacitors. Load bus voltages are fuzzified using fuzzy sets and their enforcements are maximized. Optimal reactive power planning is solved in the successive multi objective fuzzy LP network.
In [53, 2000] an interactive fuzzy norm approach is presented for solving the reactive power sources planning. In the first step weak buses are identified and selected as the candidate buses for the installation of reactive power sources. Then a fuzzy norm approach based on simulated annealing method is applied to get global non-inferior solution.

1.7 Necessity of using Non-Classical Approaches:

A common drawback of most of the classical optimization technique is their dependence on the derivatives of the objective function and the constraints. The objective function and the constraints of the reactive power optimization problem are non-differentiable because of the step like variation of the capacitor cost and the discrete nature of the capacitor and tap changer position variables. Not only the reactive power optimization, most of the engineering optimization problems are characterized by this nature of the system equations. A new class of optimization techniques, called Evolutionary Optimization Techniques have become very popular in recent years because they can handle the problems having combinational characteristics very efficiently. These methods have been developed by simulating the process of evolution existing in nature. They evaluate the objective function directly and select the search points without using the derivatives of the cost function or the constraints. Since these methods are probabilistic in nature they are more likely to converge to the global optimal solution. A number of such evolutionary algorithms have been reported in recent years followed by the development of the Genetic algorithms by John Holland in 1975 and popularized by Goldberg and other researchers. Some of the other evolutionary algorithms are evolutionary strategies, evolutionary programming, Particle Swarm Optimization, Memetic algorithms, Ant Colony Optimization and Differential Evolution. One common drawback of all of these search techniques is the slow convergence.

In recent years these algorithms have extensively been used by the researchers to solve many power system problems including the problems of reactive power optimization. In order to get rid of the curse of slow convergence, these algorithms have been modified by incorporating partially the classical optimization techniques, heuristics and fuzzy logic into the framework of the evolutionary algorithms. Some times more than
one evolutionary techniques have also been amalgamated to have a better convergence characteristics. A brief review of the works on the reactive power optimization problem utilizing the evolutionary approaches is reported below.

### 1.8 A Brief Review of the Evolutionary Solution of the reactive Power Problem

In [23, 1994] a computer package employing two stage solution algorithm based on an extended simulated annealing technique and the E – constrained method is presented. The first stage of the solution algorithm uses an extended simulated annealing technique to find a global, non-inferior solution. The second stage consists of the E – constraint method and the simulated annealing technique for the constrained single objective optimization problems. The results obtained from the first stage provide a basis for the designers to prioritize the objective functions such that a primary objective function is chosen and a trade–off tolerances for the other objective functions are set. By this way, constrained multi-objective optimization problem is transformed into a single objective optimization problem with more constraints by employing the E – constraint method. The simulated annealing technique is then applied to the single objective optimization problem to find the global optimal solution.

In [24, 1994] Genetic Algorithm is used for optimal reactive power planning. The principal features of their proposed methods are of

- Searching of multiple paths to reach a global optimal.
- Uses various objective functions simultaneously
- Treats integer / discrete variables.

In [29, 1995] the authors have presented an algorithm based on hybrid expert system simulated annealing technique for optimal reactive power planning. This technique is adopted for a constrained multi objective and non-differentiable optimization problem. There are two objective functions are minimized in this paper. The first function represents the cost of VAR source placements plus the total cost of energy loss. The second function expressed in the form of voltage deviation.

In [30, 1995] Evolutionary programming technique is applied for optimal reactive power dispatch and voltage control of power systems. The authors have shown that
results obtained after the application of EP are always better than the conventional optimization techniques.

In [31, 1995] An Improved Simple Genetic Algorithm combined with the successive linear programming technique is used for reactive power planning. The Bender's cut are constructed during the SGA procedure to enhance the robustness and reliability of the algorithm. SGA is used to select the location and the amount of reactive power sources to be installed whereas successive linearized formulation of the P – Q optimization modules speeds up computation and allows LP to be used in finding the solution of the non-linear problem.

In [35, 1996] Evolutionary programming (EP) technique is applied for reactive power planning since EP does not need to differentiate the objective function and constraints. It uses probability transition rules to select generations. Here each individual competes with other individuals in a combined population of the old generation and the mutated old generation. After comparison with a non-linear programming algorithm, the BFGS method, authors have proved superiority of the EP technique.

In [37, 1996], An EP approach has been used for solving the reactive power planning for practical power systems. The application studies on a real power system in England show the EP always leads to a global or near global optimum point of the multi objective reactive power problem under different situations.

In [40, 1997] Evolutionary programming approach to the reactive power planning is presented. Test results obtained over IEEE 30 bus is compared with Broyden's method and superiority of EP is shown.

In [42, 1997] a GA based algorithm followed by sensitivity based heuristic method is presented for capacitor placement, replacement and control problem. The GA is employed to find neighborhoods of high quality solutions and to provide a good initial guess for the sensitivity based heuristic. The heuristic uses the sensitivity of real power loss to reactive power to quickly and locally improve upon the solution provided by the GA.

In [43, 1998] Genetic Algorithm is used for reactive power dispatch. The method is used for searching transformer tap settings and shunt capacitors for minimization of total system power loss.
In [44, 1998] Genetic Algorithm based optimization technique is used for optimal control of reactive power. Here the objective function is considered as multi objective. In addition to real power loss, penalty functions for voltage and reactive violations and associated penalty factors are included in the objective function.

In [45, 1998] a comparative study of three evolutionary algorithms (EA’S) for optimal reactive power planning problem is done. IEEE 30 bus is used as test bus system. The results of three evolutionary algorithms are compared with the result obtained using LP the EA's result is always found to be better. ES needs less generation to converge but has a high probability to fall into a local minimum, the EP needs more generation to converge but less likely to fall into a local minimum, when EP is combined with ES it only needs nearly the same number of generations to converge as ES but with improved robustness in finding the global minimum.

In [46, 1998] Evolutionary programming based algorithm used for solving environmentally constrained economic dispatch problem. The algorithm can deal with load demand specifications in multiple intervals of the generation scheduling horizon.

In [48, 1998] Evolutionary programming technique is used for reactive power planning. The proposed approach has been used in a real power system in England. Simulation results compared with those obtained by using an improved Genetic Algorithm and a conventional gradient based optimization method, Broyden's method and author's have claimed that Evolutionary programming yields better result.

Capacitor placement problems in distribution systems is solved in [49, 1999] using Genetic Algorithm. The Genetic Algorithm string of the problem has been formed by location selector sub string and the size sub-strings where the location selector sub string represents the probable capacitor locations and the size-sub string represent capacitor Kvar at different locations.

Three extended algorithms based on meta evolutionary programming and evolutionary strategies are presented in [51, 1999]. A comparative study between these algorithms and LAI and MA evolutionary algorithm has been preferred.

Particle swarm optimization technique for reactive power and voltage control considering voltage security assessment is presented in [54, 2000]. Voltage security is considered using continuation power flow and a contingency analysis technique. This
method formulates voltage VAR control as a mixed integer non-linear optimization problem and control variables were chosen as continuous and discrete. The feasibility of the proposed method is demonstrated and compared with reactive tabu search.

In [56, 2001] differential evolution algorithm is implemented with search space expansion scheme for getting a globally optimal approximate models for stable / unstable and / or non minimum – phase complex systems.

In [57, 2002] a differential evolution algorithm with self adaptive crossover and mutation feature is presented. The simulation results obtained from this technique is compared with other evolutionary multi objective optimization algorithms and claimed the superiority of their technique.

In [58, 2002] an extension of the Differential Evolution (DE) algorithm for handling multiple constraint functions was proposed and demonstrated with a set of ten well known test problems. CPU time is considerably reduced. User need not require to set additional search parameters as in original DE.

Enhanced Genetic Algorithm (EGA) is applied for the solution of the optimal power flow with both continuous and discrete variables in [59, 2002]. The continuous control variables modeled unit active power outputs and generator bus voltage magnitudes while the discrete ones are transformer tap settings and switch able shunt devices. A number of functional operating constraints, such as branch flow limits, load bus voltage magnitude limits, and generator reactive capabilities are included as penalties in the GA fitness function.

Modified mixed integer hybrid differential evolution (MIHDE) method is used in [60, 2002] for the placement of capacitors in a distribution system utilizing sensitivity factors. According to the authors, this method is especially useful for large distribution system applications. From the sensitivity factors, sensitive buses are determined. Sensitive buses are those buses to which when additional capacitors are added will have greater effect in reducing power loss.

Fuzzy based reactive power and voltage control in a distribution system is presented in [61, 2003]. Here the objective function and constraints are formulated with fuzzy sets. Then a simulated annealing approach is applied to solve the fuzzy based reactive power and voltage control problem to find the optimal dispatching schedule of
main transformer LTC position and capacitors on/off status in a day. In the proposed annealing method only one variable in the solution configuration was perturbed to create a neighbor solution.

A hybrid particle swarm with differential evolution (DE) operator, termed DEPSO is described in [62, 2003]. The hybrid strategy provides the bell shaped mutation with consensus on the population diversity by DE operator, while keeps the self organized particle swarm dynamic to make it independent of the strategy parameters as in DE. This technique is not found suitable for problems with equality constraints.

In [63, 2004] hybrid evolutionary programming technique is used to solve the optimal reactive power dispatch problem. It begins with applying primal dual logarithmic barrier interior point method to obtain an optimal solution, and then the solution is runned off and introduced into initial population of EP method to continue the evolution process.

1.9 Scope of the Present Work:

Inspired by these efforts, the author of the present thesis have investigated on the applicability, efficiency and the scope of enhancement of the solution speed of some of the evolutionary algorithms in solving the reactive power optimization problem. Both the planning as well as reactive power dispatch problem have been solved and three evolutionary algorithms namely Genetic algorithm, Particle Swarm Optimization and Differential Evolution technique have been tested in solving these problems. Enhancement of the solution speed and quality have been attempted using the well known optimization techniques like linear programming and Simulated annealing techniques. Hybrid solution techniques have also been attempted using the combination of heuristic approaches along with the evolutionary techniques. The outcome of the attempts have been reported in the present thesis in the following order.

Chapter two reports the modeling of reactive power problem and applicability of evolutionary programming techniques for solution.

Chapter three reports the general formulation of the problem for solution using evolutionary algorithms. A comparison of the performance of the three different evolutionary approaches have also been reported in chapter three.
Chapter four reports the development of combined Heuristics and Evolutionary technique for the reactive power problem.

Chapter five dealt with the capacitor placement problem for the radial type distribution network using a heuristic search technique.

Finally, chapter six summarizes the achievements made by the author in course of the present work. The shortcomings of the present work and the scope for further research that can be a natural extension of the present work is also reported.