CHAPTER 1

INTRODUCTION

1.1 PREAMBLE

In the present scenario, the load density of the system has increased abnormally and due to which the quality of power has decreased. The quality of power lacks due to the shortage of reactive power during the peak load periods which results in the reduction of overall voltage level. So the Reactive Power Optimization (RPO) and voltage control are an essential topic of research. The reactive power and voltage control improves the economy and security of the power system. The load bus voltages can be maintained within the permissible limits by reallocating reactive power generation in the system which is achieved by adjusting the transformer taps, generator voltages and switchable VARs. The real power losses in the system are minimized by the redistribution of the reactive power. So the RPO problem deals with the minimization of the real power loss in the system and improvement of the voltage profile of the system. Mathematically, RPO problem is a complicated non-linear programming problem with non-linear objective functions, non-linear equality and inequality constraints.

Optimization deals with the problem of seeking solution over a set of possible choices to optimal criteria. If the criterion considered is one, it is a single objective optimization problem. If the number of criteria is more than one and if they are treated simultaneously, the problem is a Multi-Objective Optimization (MOO) problem. The MOO problem arises in the modeling and
planning of many complex real systems. The MOO problem is of interest to researches from early 1960s. The conventional RPO takes minimum power loss or voltage quality as major objectives and concerns little over the voltage stability and investment cost of the VAR sources. So RPO problem is a single objective optimization problem. The conventional RPO problem is solved using the non-linear programming technique, sensitive and gradient based techniques and heuristic techniques. The non-linear programming has various drawbacks like insecure convergence, more execution time and complexity. The sensitive and gradient based techniques get trapped in the local minima which lead to the attainment of a solution which is not optimal. The heuristic technique which is a search based technique has attained great success in solving the RPO problem.

In recent researches in order to improve the system stability and to minimize investment cost over the VAR sources the RPO is formulated with multiple objectives like average voltage deviation, voltage stability index, voltage stability margin and minimization of investment cost in addition with the minimization of active power loss. The RPO formulated with multiple objectives is called as the Multi-Objective Reactive Power Optimization problem (MORPO).

The MORPO problem is solved using various traditional methods like weighted sum method, $\varepsilon$-constraint method etc. In traditional methods, the MORPO is initially converted into a single objective and then solved using a traditional technique. The major drawback of the traditional technique is the requirement of multiple runs to reach the optimal solution. Further as there are many uncertainties in power system problems because power systems are large, complex, highly non-linear and computationally difficult environments the traditional algorithms generate weak non-dominated solution. The major difficulties of the traditional methods are the algorithm
has to be implemented many times to obtain the pareto optimal front, sensitivity to the pareto optimal front and need of some knowledge of the problem to be solved.

On the contrary, the heuristic techniques or the intelligent techniques have proved that they are efficient to eliminate the difficulties of traditional methods. The heuristic methods use a population of solution in the search, so multiple optimal solutions can be obtained in a single run by simultaneously optimizing all the objectives. The various intelligent techniques used to solve the MOO problem include Multiobjective Genetic Algorithm (MOGA), Non-dominated Sorting Genetic Algorithm (NSGA), Niched Pareto Genetic Algorithm (NPGA), Non-dominated Sorting Genetic Algorithm – II (NSGA-II), Strength Pareto Evolutionary Algorithm (SPEA). Further Multi-Objective Evolutionary Programming (MOEP), Multi-Objective Tabu Search (MOTS) and Multi-Objective Particle Swarm Optimization (MOPSO) algorithms have also been used to solve the MOO problem.

In this thesis MORPO problem is solved using EP, TS and PSO based algorithm. The results revealed that the performance of these algorithms has to be improved. So inorder to improve the performance of the algorithms, fuzzy logic has to been incorporated in the EP, TS and PSO based algorithms. Incorporation of the fuzzy logic in the search techniques avoids premature convergence and also reduces the time of computation. The incorporation of the fuzzy logic leads to the Fuzzy Mutated Evolutionary Programming (FMEP), Fuzzy Guided Tabu Search (FGTS) and Fuzzified Particle Swarm Optimization (FPSO). The MORPO is solved using the FMEP, FGTS and FPSO based algorithms

Further the performance is improved by Flexible AC transmission systems (FACTS) controllers in the MORPO problem. FACTS controllers are
thyristor based devices which are used to control the real and reactive power flow, increase transmission line stability limit, and improve the security of transmission systems. So the MORPO problem is further strengthened by including FACTS controllers. The inclusion of the FACTS controllers minimizes the system losses effectively and improves the system voltage profile.

In this thesis, the MORPO with and without FACTS controllers is formulated with multiple competent objectives like minimization of real power loss, voltage deviation, investment cost on VAR sources and voltage stability index and solved using:

- Evolutionary Programming based algorithm
- Fuzzy Mutated Evolutionary Programming based algorithm
- Tabu Search based algorithm
- Fuzzy Guided Tabu Search based algorithm
- Particle Swarm Optimization based algorithm
- Fuzzified Particle Swarm Optimization based algorithm

1.2 LITERATURE SURVEY

An exhaustive review of literature on MORPO shows that it has been formulated with various objectives in different combinations. The formulated problems were solved using various methods ranging from traditional techniques to intelligent techniques. The various search techniques like Artificial Bee Colony (ABC) Algorithm, Genetic Algorithm (GA), Ant Colony Optimization, Particle Swarm Optimization (PSO), Trust Region Algorithm, Tabu Search (TS), Differential Evolution (DE), Bacterial Swarming Algorithm (BSA), Evolutionary Programming (EP),
Simulated Annealing (SA), Seeker Optimization Algorithm (SOA), Global Best Harmony Search Algorithm and Adoptive Immune Algorithm are used to solve the MORPO problem. Moreover Multi-Objective Genetic Algorithms (MOGA), Multi-Objective Particle Swarm Optimization (MOPSO), Multi-Objective Search Oriented Algorithms (MOSO), SPEA which are efficient for MOO problems have also been used to solve the MORPO problem.

1.2.1 Genetic Algorithm

Abido et al (2003) has proposed a Niched Pareto Genetic Algorithm (NPGA) to solve the multi-objective optimization problem in a single run. A clustering algorithm is used and moreover the fuzzy set theory is employed to obtain compromised solutions.

Subramanian et al (2009) has presented an elitist Non-Dominant Sorting Genetic Algorithm Version II (NSGA-II) to solve the multi-objective optimization problem where the real power loss and the bus voltage deviations are to be minimized. Different trade-off solutions are provided as the problem is treated as a true multi-objective optimization problem. The IEEE 30-bus system is used as a test system and the results are compared with the conventional weighted sum method using Real Coded Genetic Algorithm and NSGA.

Antunes et al (2009) has modeled the problem of locating and sizing capacitors for reactive power compensation in electric radial distribution networks as a multi-objective programming problem. An elitist Genetic Algorithm with secondary population is used to characterize the Pareto optimal frontier. Minimization of system losses and minimization of capacitor installation costs are considered as objectives.
Jeyanthy et al (2010) proposed a new multi-objective genetic algorithm method to optimize the reactive power dispatch problem. The objectives of the reactive power optimization problem are minimization of the losses and maximization of the voltage stability margin. The original GA is expanded to tackle the mixed –integer non linear optimization problem with continuous and discrete control variables such as generator terminal voltages, tap position of transformers and reactive power sources. For effective genetic operation, crossover and mutation operators which can directly operate on floating numbers are used. MOGA is applied to solve this reactive power dispatch problem. The MOGA emphasizes on non-dominated solutions which are obtained by simultaneous solving of the objectives.

Li et al (2010) has improved the elitist Non-dominated Sorting Genetic Algorithm for multi-objective Optimal Reactive Power Flow problem. Multiobjective ORPF is formulated as a mixed integer non-linear optimization problem which minimizes the real power loss and improves voltage profile of power grid by determining the reactive power control variables. NSGA-II-based ORPF is tested on standard IEEE 30-bus test system and compared with four other state-of-the-art MOEAs. Pareto front and outer solutions achieved by the five MOEAs are analyzed and compared. Several problem-specific Local Search Strategies (LSSs) are incorporated into NSGA-II to improve the algorithm’s exploiting capability and convergence. The enhanced version of NSGA-II (ENSGA) is examined on an IEEE 30-bus system.

Subramanian et al (2011) has formulated the multi-objective reactive power dispatch problem as a non-linear constrained optimization problem with objectives as real power loss minimization and control variable adjustment cost. The concept of dynamic crowding distance is implemented on NSGA-II algorithm which leads to the Modified NSGA-II algorithm.
(MNSGA-II). The method is tested on standard IEEE 30-bus system and 118-bus system.

Jeyadevi et al (2011) has addressed an application of modified NSGA-II (MNSGA-II) by incorporating controlled elitism and Dynamic Crowding Distance (DCD) strategies in NSGA-II to multi-objective Optimal Reactive Power Dispatch (ORPD) problem by minimizing real power loss and maximizing the system voltage stability. The results are validated with the results obtained by weighted sum method. TOPSIS technique is applied on obtained non-dominated solutions to determine best compromise solution. Karush–Kuhn–Tucker conditions are also applied on the obtained non-dominated solutions to substantiate a claim on optimality.

Saini et al (2012) has presented an application of elitist NSGA-II algorithm for solving multi-objective reactive power market clearing model. Two objectives, namely the total payment function for reactive power supports and voltage stability enhancement index are optimized simultaneously in competitive electricity market.

Alonso et al (2012) has considered reactive power planning as a crucial issue which entails all the necessary planning actions to improve the voltage profile as well as the voltage stability in power networks. The ultimate aim in reactive power planning has been addressed as the resolution of an optimization problem, in which multiobjective optimization techniques emerge as good alternatives to fulfill several goals simultaneously. The problem is solved using GA and the performance is evaluated with several wind farms and FACTS units in an optimal location. An existing 140-bus system is used for validation.
1.2.2 **Strength Pareto Evolutionary Algorithm**

Barán et al (2001) has proposed a variant of the SPEA that independently optimizes several parameters, turning most traditional constraints into new objective functions. A Pareto set is found before deciding which solution best combines different features. The Pareto set is compared with several sets of solutions obtained by different methods with different test suite metrics.

Barán et al (2001) has formulated the reactive power optimization problem as a multi-objective optimization problem and has solved using a variant of SPEA in which pareto sets are obtained.

Abido et al (2003) has formulated the optimal VAR dispatch problem as non linear constrained multi-objective optimization problem where the real power loss and voltage deviation are to be simultaneously minimized. A new Strength Pareto Evolutionary Algorithm (SPEA) is proposed in which a hierarchical clustering algorithm is imposed to provide the decision maker with a representative and manageable Pareto-optimal set. A true well distributed pareto optimal solution is obtained in a single run.

Abido et al (2005) has formulated a nonlinear constrained multi-objective optimization problem where the real power loss and the bus voltage deviations are to be minimized simultaneously. The problem is solved using a new SPEA in which clustering algorithm and fuzzy set theory is employed to obtain manageable pareto front and compromised solution respectively.

Abido et al (2006) has presented SPEA for optimal reactive power (VAR) dispatch problem. The optimal VAR dispatch problem is formulated as a nonlinear constrained multiobjective optimization problem where the real power loss and the voltage stability are to be optimized simultaneously. The
proposed approach handles the problem as a true multiobjective optimization problem and is capable to generate true and well distributed pareto optimal solutions.

Reddy et al (2011) has presented a new multi-objective optimization based Reactive Power Price Clearing (RPPC) mechanism, considering voltage stability. Investigations have also been carried out to ascertain the effectiveness of objectives such as, Total Payment Function (TPF), Loss Minimization (LM), Load Served (LS) and Voltage Stability Enhancement Index (VSEI). The unsuitability of LM/TPF minimization as independent or joint objective(s) for this problem, due to load served reduction is emphasized. The effect of loading condition on judicious combination of these objectives is also considered. The multi-objective RPPC problem is solved using SPEA and compared with the MOPSO. The algorithm is demonstrated on a standard IEEE 30-bus system.

1.2.3 Evolutionary Programming

Ma et al (1996) has proposed an application of EP to reactive power planning problem. The reactive power problem is a nonsmooth and nondifferential optimization problem for a multiobjective function. The approach is demonstrated with a IEEE 30-bus system and the results were compared with a conventional optimization technique.

Lai et al (1997) has applied the EP to reactive power planning problem and proved that the EP algorithm is better than the nonlinear programming. The simulation results were compared with those obtained by using a conventional gradient-based optimization method. Broyden's method is presented to show that the EP is better for power system planning.
Jiang et al (2005) has presented an improved evolutionary programming method with dynamic mutation and metropolis selection to solve the multi-objective reactive power optimization under the deregulation environment. The new method accelerates the convergence and increases precision. It is proved as an efficient way to optimize the capacitor banks and the adjustable transformer ratio by testing on an IEEE 30-bus system.

Nandhakumar et al (2011) has proposed an application of Evolutionary Programming to reactive power planning problem using SVC, TCSC and UPFC. The Fast Voltage Stability Index (FVSI) is used to identify the critical lines and the buses on which the FACTS devices are to be placed. It is proved that the FACTS controllers give considerable reduction in system losses and improvement of voltage stability for the RPP problem.

1.2.4 Tabu Search

Shi et al (2005) has developed a fuzzy evaluation based multi-objective model for reactive power optimization in power distributed networks. The objectives active power loss and improvement of voltage profile are evaluated by membership functions and compared in a single scale. The weighted sum approach is used to have a compromise between the objectives. The Tabu search algorithm is employed to obtain the optimal solution. The algorithm is demonstrated on a practical power distribution network.

1.2.5 Particle Swarm Optimization

Su-hua et al (2006) has established a multi-objective model of RPO in which power loss minimization, voltage stability margin maximization and high service quality are considered as objectives. In order to measure the voltage stability, the least singular value of converged load flow Jacobian is
employed as an objective. The established problem is solved using a parallel PSO algorithm which can keep the population diversity.

Zhang et al (2008) has presented a new formulation of multi-objective reactive power and voltage control of power system. The active power loss, voltage deviation and voltage stability index of the system are considered as the objectives. The objectives and the constraints are evaluated by using membership functions. The inequality constrains are embedded into the fitness function by pseudo-goal function which guarantees that the searched optimal solution is feasible. The PSO algorithm is improved by adoptively adjusting the parameters such as inertia weight and learning factors.


Eghbal et al (2009) has developed SPEA and MOPSO approaches to treat the reactive power planning problem using multi-objective evolutionary algorithms. The problem is formulated as a nonlinear constrained multi-objective optimization problem with objectives as minimizing the total incurred cost of the VAR planning problem and maximizing the amount of Available Transfer Capability (ATC). Pareto set is obtained and encouraging results show the superiority of the proposed approaches.

Li et al (2010) has proposed a modified particle swarm optimization algorithm based on pareto solution in which the probability of falling in local minima is being restricted and the diversity of solution set is
improved. The algorithm is the combination of Tabu search and the Multi-objective PSO algorithm. The algorithm is implemented on an IEEE 30-bus system and the effectiveness is proved.

Jeyanthy et al (2010) has proposed a hybrid particle swarm optimization algorithm for solving multi-objective real power optimization problem with minimization of loss and maximization of voltage stability margin are considered as objectives. The original GA and PSO are expanded to tackle the mixed integer non-linear optimization problem and achieve the voltage stability enhancement with continuous and discrete control variables. IEEE 30-bus and 57 bus system are used an test systems inorder to prove the effectiveness of the algorithm.

Mancer et al (2012) has proposed an efficient variant of PSO to solve the multi-objective optimal power flow based FACTS using multiple STATCOM controllers. The MORPO is considered with two objectives the power loss and the voltage deviation.

Mancer et al (2012) has proposed a new variant of PSO algorithm with varying acceleration co-efficients to solve the MOORPF with power loss and voltage deviation as objective functions. The parameters of TCSC has been dynamically controlled in coordination with the generating units.

1.2.6 Other Algorithms

Hsaio et al (1994) has developed a computer package for multi-objective VAR planning in large scale power systems. The optimal VAR planning is reformulated as a constrained, multi-objective, non-differentiable optimization problem. The four different objective functions related to system investment, system operational efficiency, system security and system service quality. The load, operation and contingency
constraints are also considered. Both the objective functions and equality and inequality constraints are non-differentiable. A two-stage solution algorithm based on an extended simulated annealing technique and the C- constraint method is used to solve the formulated problem.

Zhen et al (2007) has handled the multi-objective optimization problem with real power losses and voltage stabilities to be simultaneously optimized with the Bacterial Swarming Algorithm (BSA). IEEE 30-bus system has been used to evaluate the algorithm and the results demonstrate the capabilities of generating solutions superior than the conventional weighted sum based methods.

Xiong et al (2008) has proposed an Optimal Reactive Power Flow (ORPF) incorporating static voltage stability based on a Multi-Objective Adaptive Immune Algorithm (MOAIA). Two parts have been added to an existing immune algorithm. The first part defines both partial affinity and global affinity to evaluate the antibody affinity to the multi-objective functions. The second part uses adaptive crossover, mutation and clone rates for antibodies to maintain the antibodies diversity. The proposed algorithm has achieved a dynamic balance between individual diversity and population convergence. The MOAIA method has been tested in an IEEE-30 system and compared with the results obtained from IGA (Immune Genetic Algorithm). The results show the improved performance of MOAIA over IGA.

Zhang et al (2009) has presented a novel algorithm which deals with the multi-objective reactive power optimization problem called as the Multi-Objective Oriented Search Algorithm (MOOSA). The algorithm has strong ability to search optimal solutions and well distributed solutions in pareto front.
Dai et al (2009) has proposed a Seeker Optimization Algorithm (SOA) based method for ORPD considering static voltage stability and voltage deviation. The SOA is based on the concept of simulating the act of human searching where search direction is based on the empirical gradient by evaluating the response to the position changes and step length is based on uncertainty reasoning by using a simple fuzzy rule. The results obtained are compared with two versions of GAs, three versions of DE algorithms and four versions of PSO algorithms on the IEEE 57-bus system and IEEE 118-bus system.

Ozturk et al (2010) has used multi-objective reactive power optimization considering voltage deviation of buses, active power loss and reactive power generation cost. The new metaheuristic optimization method, Artificial Bee Colony is used as an optimization technique. The results were obtained by implementing on a 10-bus system and compared with the results of SPEA.

Shariatmadar et al (2010) has considered the reactive power optimization with objectives such as decreasing power loss of the system, increasing voltage stability and also decreasing voltage deviation of buses. A compromising multi-objective approach and the global best harmony search algorithm has been used to solve the reactive power control problem optimization problem. The IEEE 57-bus system has been used as the test system and the results were compared with the other optimization algorithms to show the effectiveness of the proposed algorithm.

Jaganathan et al (2011) has proposed an ant colony algorithm for solving an MORPO problem in which the power loss and the voltage stability are simultaneously optimized. A hierarchical clustering algorithm is used to provide the decision maker with a representative and manageable Pareto optimal set.
Antunes et al (2011) has presented a multi-objective simulated annealing approach to provide decision support in sizing and location of capacitors, releasing system capacity and improving voltage level. A set of well-distributed and diversified solutions underlying distinct trade-offs is obtained.

Prajapati et al (2012) proposed Artificial Bee Colony (ABC) based algorithm to handle the RPO problem as a true multi-objective optimization problem with competing and non-commensurable objectives. The objective considered are the reduction of real power loss and improvement of voltage profile. The colony of the bees consists of three kinds of bees namely employed bees, onlookers and scouts.

El-sobky et al (2012) has introduced a trust region algorithm for solving a reactive power compensation problem in a multi-objective context. The proposed approach is suitable for reactive power compensation problems where the objective function may be ill-defined, having a non-convex pareto-optimal front.

Zhang et al (2012) has employed Dynamic Multi-group Self adoptive Differential Evolution (DMSDE) algorithm to solve the multi-objective reactive power optimization problem. The population is divided into multiple groups which exchange information dynamically and in the mutation phase, the best vector among the three randomly vectors is used as the base vector while the difference vector is determined by the remaining two vectors. The parameters, F and CR, are self-adapted. The proposed method is tested on IEEE 30-bus and a practical Indian power systems.

From the above exhaustive literature review certain limitations of the EP, TS and PSO based algorithms are summarised as follows:
(i). The convergence is very slow, as these algorithms are random search techniques, and they have to handle multiple objectives with enormous decision variables.

(ii). In the mutation process of EP and TS, the value of variance depends on the factors namely relative fitness, search range and scaling factor. It is inferred that the search range is a constant throughout the search process, thus there is a possibility of slow convergence.

(iii). In most of the methods, the optimal solutions are obtained in any way by weakening one or more objectives. So, a diverse optimal solution has to be determined.

The literature review reveals that there exists a need for evolving a simple, effective and faster algorithm for solving MORPO. The algorithm should have the ability to generate multiple Pareto sets at a single run. In addition the algorithm should obtain the optimum results with faster convergence. Hence, in this work, an attempt has been made to solve the MORPO problem with and without FACTS controllers, by using Fuzzified EP, TS and PSO based algorithm which are able to find diverse solutions.

1.3 OBJECTIVES OF THE THESIS

The main objectives of this thesis are:

(i) to formulate the MORPO problem with competing objectives namely the minimization of real power loss, voltage deviation, investment on VAR sources and the voltage stability index.

(ii) to propose certain improved stochastic optimization techniques namely FMEP, FGTS and FPSO for solving the
MORPO problem and to evaluate the performance of the algorithms by their optimal results, convergence characteristics and Pareto fronts.

(iii) to solve the MORPO problem with various FACTS controllers using the proposed improved stochastic algorithms.

1.4 OUTLINE OF THE THESIS

A brief outline of the various chapters is as follows:

In chapter 2, a fundamental knowledge of Multi-Objective Optimization (MOO) problem and the various methods to solve it are discussed. The Multi-Objective Reactive Power Optimization (MORPO) problem is formulated with objectives namely, minimization of active power loss, voltage deviation, minimization of the investment cost on VAR sources and voltage stability index subjected to equality and inequality constraints.

In chapter 3, a brief description to the Evolutionary Programming for solving MOO is presented. Then the performance of the EP is improved by incorporating the fuzzy logic. The MORPO problem with objectives namely active power loss, voltage deviation and investment cost on VAR sources is solved using the EP and FMEP based MOO algorithms. An IEEE 30-bus system is used as a test system to investigate the performance of EP and FMEP based algorithm on MORPO problem. The optimal result obtained is compared with the results of SPEA from the literature. The convergence characteristics and the Pareto fronts of the EP and FMEP based algorithms for MORPO problem are figured.

Chapter 4, a brief introduction to the TS algorithm and the method to handle the MOO problem with TS algorithm is presented. The TS for MOO problem is used to solve the MORPO problem with competing objectives
namely the real power loss, voltage deviation and the investment cost. The performance of the TS based algorithm for MOO problem is improved by incorporating fuzzy logic in the mutation and recombination process which leads to FGTS algorithm. The TS and FGTS based algorithm are implemented on IEEE 30-bus system and 66-bus practical Indian system. The results, convergence characteristics and the Pareto fronts obtained are compared with the EP and FMEP based algorithms for MORPO.

In chapter 5, an introduction to the PSO is presented and PSO based algorithm for solving MOO problem is explained. The PSO based algorithm for MOO problem is used to solve the MORPO problem with objectives namely the real power loss, voltage deviation and the voltage stability index. The convergence characteristic is improved by incorporating fuzzy logic in the determination of adoptive weight which leads to the FPSO. The FPSO and PSO based algorithms for MORPO problem is implemented on IEEE 30-bus system, 66-bus practical Indian system and IEEE 118-bus system. The results, convergence characteristics are compared with EP, FMEP, TS and FGTS based algorithms for MORPO problem. The Pareto fronts obtained by TS and FGTS based algorithm for MORPO problem is given.

In chapter 6, an overview of the FACTS controllers namely SVC, TCSC and UPFC and their power flow models along with the method of incorporation is presented. The MORPO problem is included with the FACTS controllers to improve the performance of the system. The MORPO problem with FACTS controllers are solved with the EP, FMEP, TS, FGTS, PSO and FPSO based algorithms. The results obtained are compared with the results obtained without FACTS controllers.

In chapter 7, a review of the work carried out, the contributions made and the major conclusions are highlighted. The scope for further work is also listed.