

**MULTI-OBJECTIVE OPTIMAL POWER FLOW SOLUTION USING GENETIC
ALGORITHM**

A thesis submitted in partial fulfilment of the requirement for the award of degree of

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in
Power Systems & Electric Drives



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CERTIFICATE

I hereby certify that the work which is being presented in the thesis entitled, “**Multi-Objective Optimal Power Flow Solution using Genetic Algorithm**”, in partial fulfilment of the requirements for the award of degree of Master of Engineering in Power Systems & Electric Drives submitted in Electrical & Instrumentation Engineering Department of Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of *Mr. Parag Nijhawan*, Assistant Professor. The matter presented in this thesis has not been submitted for the award of any other degree of this or any other university.


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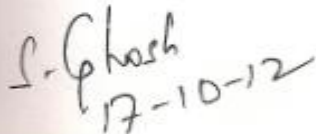

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ABSTRACT

The main function of Optimal Power Flow (OPF) solution is to minimize the fuel cost, losses and fuel emissions (NO_x , SO_x and CO_x) while the system is operating within its security limits. This solution can be applied on problem involving either a single objective function or multiple objective functions.

Even though, excellent advancements have been made in classical methods, they suffer from disadvantages because of the extremely limited capability to solve real-world large-scale power system problems. They are weak in handling qualitative constraints. The major advantage of the GA is that it is relatively versatile for handling various qualitative constraints. It can find multiple optimal solutions in single simulation run. So they are quite suitable in solving multi-objective optimization problems.

In this thesis, Genetic Algorithm (GA) based multi-objective optimal power flow (OPF) solution is obtained for the IEEE 30-bus 6-generator system.

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CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

The environmental pollution is increasing day by day due to industrial advancement. Although with the advancement in technology, economic development is improved but at the same time results in enormous emission of harmful products and wastes. For example, thermal power plants pollute air, water and soil. The combustion of fossil fuels gives rise to particulate material and gaseous pollutants along with heat. Oxides of carbon (CO_x), oxides of sulphur (SO_x) and oxides of nitrogen (NO_x) are the main gaseous pollutants that cause harmful effects on environment including human beings. Thus this leads to an urgent need for optimum operating strategy, which can ensure minimum pollution level at minimum operating cost.

With the growing demand on electric power and the increase of fuel oil prices, power utilities worldwide are working to provide their customers with a continuous supply of energy at competitive prices. One of the applications that help in achieving this goal is the Optimal Power Flow (OPF) program. Optimal Power Flow Dispatching (OPFD) is an optimization problem that consists of minimizing the total generation dispatch cost while satisfying physical and technical constraints on the network.

The objective of an Optimal Power Flow (OPF) algorithm is to find steady state operation point which minimizes generation cost, loss etc. or maximizes social welfare, loadability etc. while maintaining an acceptable system performance in terms of limits on generators' real and reactive powers, line flow limits, output of various compensating devices etc[1].

In any power system, unexpected outages of lines or transformers occur due to faults or other disturbances. These events, referred to as contingencies, may cause significant overloading of transmission lines or transformers, which in turn may lead to a viability crisis of the power system. The principle role of power system control is to maintain a secure system state, i.e., to prevent the power system, moving from secure state into emergency state over the widest range

of operating conditions. Optimal Power Flow (OPF) is major tool used to improve the security of the system.

The optimal power flow has been frequently solved using classical optimization methods. The OPF has been usually considered as the minimization of an objective function representing the generation cost and/or the transmission loss [2].

Optimal power flow (OPF) problem is the perfect incorporation of the contradictory doctrines of maximum economy, safer operation and security. OPF refers to the generator dispatch and resulting AC power flows at minimum and feasible cost with respect to thermal limits on the AC transmission lines. The OPF might include other constraints such as interface limits and other decisions such as the optimal flow on DC lines and phase shifter angles. 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. In general, OPF problem is a large dimension nonlinear, non-convex and highly constrained optimization problem.

Thus the optimal power flow solution is a program for scheduling power generation in such a way to minimize the fuel cost. The optimal power flow is used to achieve the following benefits:

1. Cost saving
2. Reduced system loss
3. Improved voltage control
4. Improved system security

Since the introduction of OPF in 1968 [2],[4], several methods have been employed to solve this problem, *e.g.* Gradient base[2], Linear programming method [3] and Quadratic programming [5]. However, all of these methods suffer from three main problems. Firstly, they may not be able to provide optimal solution and usually getting stuck at a local optimal. Secondly, all these methods are based on assumption of continuity and differentiability of objective function which is not actually allowed in a practical system. Finally, all these methods cannot be applied with discrete variables, which are transformer taps.

Even though, excellent advancements have been made in classical methods, they suffer from disadvantages because of the extremely limited capability to solve real-world large-scale power system problems. They are weak in handling qualitative constraints. The major advantage of the GA is that it is relatively versatile for handling various qualitative constraints. It can find multiple optimal solutions in single simulation run. So they are quite suitable in solving multi-objective optimization problems.

It seems that GA is an appropriate method to solve this problem, which eliminates the above drawbacks. Holland is the grandfather of the field that became Genetic Algorithms. Holland investigated adaptive systems in the late 1960s proposing adaptive system formalism and adaptive strategies referred to as ‘adaptive plans’ [6]. GA, invented by Holland, is a stochastic global search method that mimics the metaphor of natural biological evaluation.

Genetic Algorithms (GAs) operates on a population of candidate solutions encoded to finite bit string called chromosome. In order to obtain optimality, each chromosome exchanges the information using operators borrowed from natural genetic to produce the better solution

Few examples of OPF applications are:

- Voltage Instability, Maximum transfers (V-P Curve Approach) or minimum compensation requirements (Q-V Curve Approach) to attain voltage stability are obtained in a single solution. Other constraints such as voltage and/or thermal limitations can be added.
- Reactive power compensation using capacitors, reactors or Flexible AC Transmission Systems (FACTS). OPF will likely be used to dispatch the transmission network (e.g., series and shunt compensation) to overcome post disturbance thermal and voltage violations.
- Economic dispatch, subjected to thermal constraints, voltage constraints, interface constraints (e.g., stability) and spinning reserve constraints. From this dispatch, marginal costs and transmission bottlenecks are easily identified.

When an optimization problem involves more than one objective function, the task of finding one or more optimum solutions is known as multi-objective optimization [7]

1.2 OBJECTIVE OF THE WORK

The aim of this proposed work is to carry out multi-objective optimization for minimizing the fuel cost and fuel emission, while satisfying the various equality and inequality constraints. In this thesis, Genetic Algorithm is used to solve the single-objective and multi-objective OPF problem for the IEEE-30 bus system.

1.3 ORGANIZATION OF THESIS

Chapter 1: It gives the overview of this thesis. Here a literature review is done on the Optimal Power Flow along with that of Genetic Algorithm. Then finally the objective of thesis work has been added.

Chapter 2: In this introduction to OPF is given. OPF formulation for minimizing objectives like generation cost and fuel emissions is described in this chapter.

Chapter 3: It contains detailed theory about Genetic Algorithm. Its history, operators and applications. It contains its flowchart also.

Chapter 4: This chapter revolves around single-objective OPF solution based on GA. In this, objective functions like generating cost, fuel emissions (CO_x , NO_x and SO_x) are solved separately as single-objective functions.

Chapter 5: It explains the multi-objective OPF using GA in MATLAB environment to minimize different objective functions like generating cost, fuel emissions (CO_x , NO_x and SO_x). The results have been discussed.

Chapter 6: Finally, the conclusion of entire work done has been added. Also, scope of further work in this field has been included in this chapter.

1.4 LITERATURE REVIEW

In recent years, there has been an increase in research on Optimal Power Flow (OPF). Vast literature is available for OPF. The objective of an Optimal Power Flow (OPF) algorithm is to find steady state operation point which minimizes generation cost, loss etc. or maximizes social

welfare, loadability etc. while maintaining an acceptable system performance in terms of limits on generators' real and reactive powers, line flow limits, output of various compensating devices etc. Survey on various OPF methods has been discussed in [1].

[2] and [4] presented the solution of optimal power flow problem of large distribution systems via a simple genetic algorithm. The objective is to minimize the fuel cost and keep the power outputs of generators, bus voltages, shunt capacitors/reactors and transformers tap-setting in their secure limits. CPU times can be reduced by decomposing the optimization constraints to active constraints manipulated directly by the genetic algorithm, and passive constraints maintained in their soft limits using a conventional constraint load flow. The IEEE 30-bus system has been studied to show the effectiveness of the algorithm. Developments in Linear-Programming based Optimal Power Flow have been described in [3]. A fresh attempt was made to develop a new algorithm for optimal power flow (OPF) using Fletcher's quadratic-programming method [5]. The new algorithm considers two decoupled sub-problems needing minimum cost of generation and minimum system-transmission losses. These have been solved sequentially to achieve optimal allocation of real and reactive power generation and transformer tap settings with consideration of system-operating constraints on generation, bus-bar voltage and line-flow limits. The potential of the new algorithm for OPF has been demonstrated through system studies for two IEEE test systems and an Indian system. Results reveal that the proposed new algorithm has potential for online solving of OPF problems.

Holland investigated adaptive systems in the late 1960s proposing adaptive system formalism and adaptive strategies referred to as 'adaptive plans' [6]. GA, invented by Holland, is a stochastic global search method that mimics the metaphor of natural biological evaluation. When an optimization problem involves more than one objective function, the task of finding one or more optimum solutions is known as multi-objective optimization [7].

In [8] and [12], an efficient and reliable evolutionary programming algorithm for solving the optimal power flow (OPF) problem has been discussed. The class of curves used to describe generator performance does not limit the algorithm and the algorithm is also less sensitive to starting points. To improve the speed of convergence of the algorithm as well as its ability to handle larger systems, the algorithm is enhanced with gradient information. In the paper, the main elements of the evolutionary programming based OPF algorithm are presented. The algorithm is then demonstrated on the IEEE 30 bus test system.

Carpentier [10] introduced a generalized formulation of the economic dispatch problem including voltage and other operating constraints. This formulation was named as the Optimal Power Flow Problem [11] gave realistic method for solving the power flow programs with control variables such as real power, reactive power and transformer ratios automatically adjusted to minimize instantaneous costs or losses. A Newton-based optimal power flow (OPF) is developed for implementation into a power system simulation environment [13]. In this paper[16] challenges to optimal power flow have been studied.

The Genetic Algorithm is characterized in [17] and [18].Improved genetic algorithms for optimal power flow under both normal and contingent operation states electrical power & energy system. In [20] neural networks, fuzzy logic, and genetic algorithm synthesis and applications have been studied. The objective of the paper [21] is to develop an algorithm to simultaneously find the real power allocation of generators and to choose the best location of UPFC such that overall cost function which includes the generation cost of power plants and investment cost of UPFC is minimized. The combinatorial analysis is solved using Genetic Algorithm and Newton Raphson's load flow method. [22]-[24] discussed the OPF using Genetic Algorithm and Evolutionary Programming. In other words, assuming an initial random population produced and evaluated, genetic evolution takes place by means of three basic genetic operators:

- 1) Parent selection
- 2) Crossover
- 3) Mutation

Many engineering problems have multiple objectives, including engineering system design and reliability optimization. There have been several interesting and successful implementations of multi-objective GA for this class of problems [26]. In response to public awareness of the environmental situation, many engineers came up with new methods to reduce air pollution keeping it economical as well. Therefore lot of research work is being done to handle such conflicting situations through multi-objective optimization [27]. The objective of paper [28] is present an overview and tutorial of multiple-objective optimization methods using genetic algorithms (GA). For multiple-objective problems, the objectives are generally conflicting, preventing simultaneous optimization of each objective. Many, or even most, real engineering

problems actually do have multiple objectives, i.e., minimize cost, maximize performance, maximize reliability, etc. These are difficult but realistic problems. GA are a popular meta-heuristic that is particularly well-suited for this class of problems. Traditional GA is customized to accommodate multi-objective problems by using specialized fitness functions and introducing methods to promote solution diversity. Most multi-objective meta-heuristics [29][30] (Meta-heuristics methods include: genetic algorithms, ant colony optimization, simulated annealing, scatter search, etc.) have been derived from their single-objective counterparts using three different approaches namely weighted sum of objectives, alternate objectives , and Pareto ranking. Weighted sum of objectives approach has been discussed in [31].

2.1 INTRODUCTION TO OPTIMAL POWER FLOW

The main purpose of optimal power dispatch problem has so far been confined to minimize the total generation cost of a power system. However, in order to meet environmental regulations enforced in recent years, emission control has become one of the important operational objectives. In addition, the passage of the clean Air Act Amendments of 1990 due to the increasing public awareness of the environmental protection, have resulted in modification of the design or operational strategies of the utilities to reduce pollution and atmosphere emissions of thermal plants[8].

System security is another important factor in power system operation and in system planning. Thus, it becomes very essential to maintain good voltage profiles and to limit line flows within the prescribed limits.

OPF [9] is a nonlinear programming problem, and is used to determine optimal outputs of generators, bus voltage and transformer tap, setting in power system. The objective of an Optimal Power Flow (OPF) algorithm is to find steady state operation point which minimizes generation cost, loss etc. or maximizes social welfare, loadability etc. while maintaining an acceptable system performance in terms of limits on generators' real and reactive powers, line flow limits, output of various compensating devices etc. The constraints involved are the physical laws governing the power generation-transmission systems and the operating limitations of the equipment.

Since its introduction as network constrained economic dispatch by Carpentier [10] and its definition as optimal power flow (OPF) by Dommel and Tinney [11], the OPF problem has been the subject of intensive research. The OPF optimizes a power system operating objective function (such as the operating cost of thermal resources) while satisfying a set of system operating constraints, including constraints dictated by the electric network. OPF has been widely used in power system operation and planning.

OPF programs based on mathematical programming approaches are used daily to solve very large OPF problems. However, they are not guaranteed to converge to the global optimum of the general non-convex OPF problem, although there exist some empirical evidence on the uniqueness of the OPF solution within the domain of interest.

2.2 OBJECTIVES OF OPF

The objectives, that the OPF will need to accomplish, are discussed here. The primary goal of a generic OPF is to minimize the costs of meeting the load demand for a power system while maintaining the security of the system. The costs associated with the power systems may depend on the situation but in general they can be attributed to the cost of generating power (megawatts) of each generator.

From the viewpoint of an OPF, the maintenance of system security requires keeping each device in the power system within its desired operation range at steady state. This will include maximum and minimum output for generators, maximum MVA flows on transmission lines and transformers, as well as keeping the system bus voltages within the specified ranges. It should be noted that the OPF only addresses steady state operation of the power system [12] and [10].

The standard OPF problem can be written in the following form

$$\text{Min. } F(x)$$

Subject to:

$$h(x) = 0 \text{ and } g(x) \geq 0$$

Where, $F(x)$ is the objective function, $h(x)$ is the equality constraints and $g(x)$ is the inequality constraints. And x is the vector of control variables (like generated active and reactive power, generation bus voltage magnitudes, transformer taps etc). The essence of the optimal power flow problem resides in reducing the objective function and simultaneously satisfying the load flow equations (equality constraints) without violating the inequality constraints [13-15].

2.3 OPTIMAL POWER FLOW FORMULATION

The most commonly used objective in the OPF problem formulation is the minimization of total cost of real power generation. The individual costs of each generating unit are assumed to be function, only of active power generation and are represented by quadratic curves of second order. The optimal power flow problem can be defined by specifying the following five attributes and can be explained as:

1. Objective function
2. The controls
3. The dependent variables
4. The equality
5. Inequality constraint

2.3.1 OBJECTIVE FUNCTION

The objective function of entire power system can then be written as the sum of the quadratic cost model at each generator.

$$F_i = a_i + b_i P_{gi} + c_i P_{gi}^2$$

where,

$$i = 1, 2, 3, \dots, ng.$$

ng = number of generators including the slack bus,

P_{gi} is the generated active power at bus i.

a_i, b_i, c_i are the unit costs curve for i^{th} generator

2.3.2 VARIABLES

Following are the variables used in formulation of OPF:

Control Variables:

The control variables in an optimal power flow problem are the quantities whose value can be adjusted directly to help minimize the objective function and satisfy the constraints. The control variables can be given as:

1. Active power generation
2. Reactive power generation
3. Transformer tap ratio
4. Generator bus voltage.

Different classes of the optimal power flow problem restrict the quantities that can be controlled. For instance an OPF algorithm for minimizing the active power generation cost might limit the controls to active power generation. The aim of the OPF is to adjust the control variables in order to minimize the total operating cost of meeting the particular load demand for a power system

Dependent Variables:

These variables are the optimal power flow variables that are not control. These include all type of variables that are free, within limits, to assume value to solve the problem. The main dependent variables are the complex bus voltage angles and magnitude.

2.3.3 CONSTRAINTS

The cost is optimized with the following constraints.

2.3.3.1 Equality Constraints

In order to minimize the equation, it is essential to know that whether the power system is running under normal conditions, i.e. load and losses i.e. power demand is satisfied and the network components are operating within limits. This can be achieved by the active and reactive power analysis:

$$P_i = P_{Load} + P_{Loss}$$

$$Q_i = Q_{Load} + Q_{Loss}$$

Where,

P_i & Q_i are the active and reactive power outputs.

P_{Load} & Q_{Load} are the active and reactive load power.

P_{Loss} & Q_{Loss} are the active and reactive power loss.

The power flow equations of the network can be given as:

$$G(V, \delta) = 0$$

where,

$$g(V, \delta) = \{ P_i(V, \delta) - P_i^{net} \\ \{ Q_i(V, \delta) - Q_i^{net}$$

where,

P_i & Q_i are the calculated real and reactive power at PQ bus

P_i^{net} & Q_i^{net} are the specified real and reactive power for the PQ bus

V & δ are the magnitude and phase angle of voltage at different buses.

2.3.3.2 Inequality Constraints

In a power system components and devices have operating limits, & these limits are created for the security constraints. Thus the required objective function can be minimized by maintaining the network components within the security limits. This brings the concept of inequality constraints. The most usual type of inequality constraints are the upper bus voltage limits at generation at load buses, lower bus voltage limits at generation at load buses, lower bus voltages limits at some generators, maximum line loading limits and limits on tap setting .These includes the following:

The inequality constraints on real power generation at i^{th} bus:

$$P_{gi}^{min} \leq P_{gi} \leq P_{gi}^{max}$$

P_{gi}^{min} & P_{gi}^{max} are the max and min value of real power generation at i^{th} bus.

The inequality constraints on reactive power generation Q_{gi} at each PV bus:

$$Q_{gi}^{\min} \leq Q_{gi} \leq Q_{gi}^{\max}$$

Q_{gi}^{\min} & Q_{gi}^{\max} are the maximum and minimum values of reactive power generation at PV bus.

The inequality constraint on Voltage magnitude V of each PQ bus:

$$V_i^{\min} \leq V_i \leq V_i^{\max}$$

V_i^{\min} & V_i^{\max} are the maximum and minimum values of voltage at bus i .

The inequality constraints on phase angle δ of voltages at all buses i :

$$\delta_i^{\min} \leq \delta_i \leq \delta_i^{\max}$$

δ_i^{\min} & δ_i^{\max} are the maximum and minimum values of the phase angle at buses i .

The inequality constraints on MVA flow limit:

$$MVA_{ij} \leq MVA_{ij}^{\max}$$

MVA_{ij}^{\max} = MVA rating of transmission line connecting i^{th} and j^{th} bus.

2.4 APPLICATIONS OF OPF

The various applications of OPF are described as [16]:

- 1) Base-case development: This is the most common application of the OPF. Dozens of base cases can be efficiently developed by following the same set of design rules.
- 2) Voltage Instability, Maximum transfers (V-P Curve Approach) or minimum compensation requirements (Q-V Curve Approach) which are to attain voltage stability can be obtained in a single solution. Other constraints such as voltage and/or thermal limitations can also be considered.

- 3) Flexible AC Transmission Systems (FACTS): OPFs will likely be used to “dispatch” the transmission network (e.g., series and shunt compensation) to overcome post-disturbance thermal and/or voltage violations
- 4) Economic dispatch, subject to: thermal constraints, voltage constraints, interface constraints (e.g., stability) and spinning reserve constraints. From this dispatch, marginal costs and transmission losses are easily identified.

3.1 INTRODUCTION

GA is a general purpose optimization algorithm based on the mechanics of natural selection and genetics.

3.1.1. Basic features of GA:

- GA is a branch of artificial intelligence.
- Artificial intelligence is an area of computer science that is concerned with the designing of intelligent computer system which exhibits the characteristics of intelligence in human behaviour.
- It belongs to the category of random search algorithms which simulate the evolution process based on the theory of survival of the fittest.
- This branch is also related with the automation of intelligent behaviour.
- GA is best suited for complex problems.
- Moreover it produces high quality solution.
- In the artificial intelligence we generally go for the probabilistic reasoning and it is predominately known as soft computing. The term soft computing was introduced by Lotif A. Zadeh of the University of California. According to him soft computing differs from the convention computing (Also known as hard computing) in its tolerance to imprecision, uncertainty and partial truth. Conventional computing is more oriented towards the mathematical approaches and therefore demands a high degree of precision. Whereas the soft computing basically inherent the characteristics of biological system and basically consist of Neural Networks (NN), Fuzzy Logic (FL) and Genetic algorithm (GA).
- Genetic algorithms are basically a family of computational models which are inspired by the biological evolution. These algorithms encode a potential solution to a specific

problem on a simple chromosome like data structure and apply genetic operators to these structures so as to preserve critical information.

- Genetic algorithms are often seen as a function optimizer.
- Genetic algorithms can be applied to a wide range of problems.
- In order to solve the problem by genetic algorithm the first step is to create the population (random) of chromosomes. Then these chromosomes are evaluated in such a way that the chromosome which represents a better solution for the problem will be given more chances than the poorer solution.
- The genetic algorithms are part of the evolutionary algorithms family, which are computational models, inspired in the Nature.

- GAs are more flexible than most search methods because they require only information concerning the quality of the solution produced by each parameter set (objective function values) and not like other optimization methods which require derivative information, or worse yet, complete knowledge of the problem structure and parameters[2].

There are some difference between GA's and other optimization/traditional searching algorithms [14] and [17-19]. They are summarized as follows

- 1) GAs work with a coding of the parameter set, not the parameters themselves. Therefore GAs can easily handle the integer or discrete variables.
- 2) GAs search within a population of points, not a single point. Therefore GAs can provide a globally optimal solution.
- 3) GAs use only objective function information, not derivatives or other auxiliary knowledge. Therefore GAs can deal with the non-smooth, non-continuous and non-differentiable functions which are actually exist in a practical optimization problem.
- 4) GAs use probabilistic transition rules, not deterministic rules, Although GAs seem to be a good method to solve optimization problem, sometimes the solution obtained from GAs is only a near global optimum solution.

3.2. INSPIRATION

The Genetic Algorithm is inspired by population genetics (including heredity and gene frequencies), and evolution at the population level, as well as the Mendelian understanding of the structure (such as chromosomes, genes etc.) and mechanisms (such as recombination and mutation). This is the so-called new or modern synthesis of evolutionary biology.

3.3. STRATEGY

The objective of GA is to maximize the payoff of candidate solutions in the population against an objective function from problem domain. The strategy for the GA is to repeatedly employ surrogates for the recombination and mutation genetic mechanisms on the population of candidate solutions, where the objective function applied to a decoded representation of a candidate governs the probabilistic contributions a given candidate solution can make the subsequent generation of candidate solutions.

3.4. HISTORY OF GENETIC ALGORITHM

John Holland is considered as the father of Genetic Algorithm. He invented it in the early 1970's and thereafter he and his students contribute much to the development of this field. Holland research was not focused on optimization and domain specific practical problem but was on the concept of adaptation as seen in nature [6] and [7]. Other important contributions were made by Frantz in 1972 who investigated what were referred to as Genetic Algorithm for Search and in 1971 Hollstien investigated genetic plans for adaptive control and function optimization. Many people included biologists, are astonished that life at the level of complexity that we observe could have evolved in the relatively short time suggested by the fossil record [20].

Many human inventions were inspired by the natural selection. Genetic algorithm is one of them. The main idea of this is the survival of the fittest or in other words it is known as natural selection. As obviously in nature the individual that has better chances for survival will survive

for a longer period of time. This in turn provides a better chance to produce offspring with its genetic material. In other words we can say that the fittest candidate will survive and unfit will not. This force of nature is called natural selection and on this principle GA works for solving optimization problems.

As we are saying that the genetic algorithm is related with the nature, so there is some analogy between them and this can be described as:

Table 3.1: Analogy between GA and Nature

GENETIC ALGORITHM	NATURE
Optimization Problem	Environment
Feasible problem	Individuals living in that environment
A set of feasible solution	Population of organism
Fitness function	Individual degree of adaptation
Operators used for results	Selection, recombination, mutation in nature

3.5. OPERATORS OF GA

GA start with random generation of initial population and then the selection, crossover and mutation operations are carried out until best population is found. Gas are simple and practical algorithm and easy to be implemented in power system [21].

In other words, assuming an initial random population produced and evaluated, genetic evolution takes place by means of three basic genetic operators [22].

- 1) Parent selection.
- 2) Crossover.
- 3) Mutation.

The details of these genetic operators are given below [23]:

1) Parent Selection/Selection Strategy:

The selection of parents to produce successive generations plays an important role in the GA. This allows the fitter individuals to be selected more often to reproduce. There are a number of selection methods proposed in the literature [24].

In this method, n individuals are copied at random from the population and the best of the n is inserted into population for further genetic processing. This procedure is repeated until the mating pool is filled.

2) Crossover:

Crossover is an important operator of the GA. The main objective of crossover is to reorganize the information of two different individuals and produce a new one. It is a structured, yet randomized mechanism of exchanging formation between strings. It promotes the exploration of new regions in search space. Cross swapping operator is applied on the selected individuals.

Here, two different cross sites of parent chromosomes are chosen at random. The cross over operation is completed by exchanging the middle substring between strings.

CROSSOVER POINT

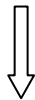


Parent 1	1	0	0	1		0	1	0	0	1	0
Parent 2	0	1	0	1		1	1	1	0	1	1
Child 1	1	0	0	1		1	1	1	0	1	1
Child 2	0	1	0	1		0	1	0	0	1	0

3) Mutation:

Mutation consists of protecting the process of reproduction and crossover effectively without much loss of the potentially useful genetic material. Mutation is by itself a random walk through the string space and provides for occasional disturbances in the crossover operation by inserting one or more genetic elements during reproduction. This operation ensures diversity in the genetic strings over long period of time and prevents stagnation in the evolution of optimal individuals. Bit wise mutation changes 1 to 0 and vice-versa. The above mentioned operations of selection, crossover and mutation are repeated until the best individual is found.

MUTATION POINT



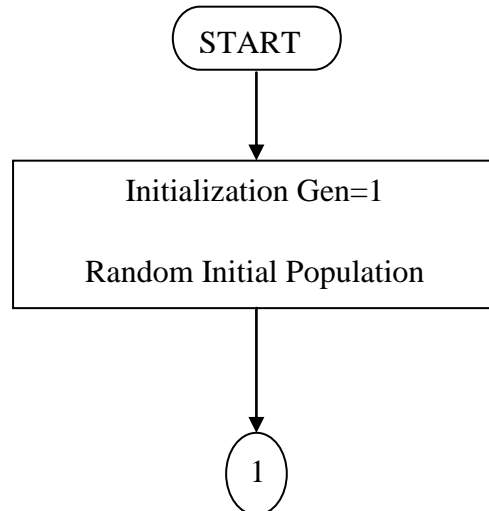
Before Mutation	1	1	0	1	0	1	0	0	1	0
After Mutation	1	1	0	1	0	1	0	1	1	0

3.6. ALGORITHM

A simple genetic algorithm of above discussion is given as follow:

1. Generate randomly a population of binary string
2. Calculate the fitness for each string in the population
3. Create offspring strings through reproduction, crossover and mutation operation.
4. Evaluate the new strings and calculate the fitness for each string (chromosome).
5. If the search goal is achieved, or an allowable generation is attained, return the best chromosome as the solution; otherwise go to step 3.

3.7. FLOWCHART



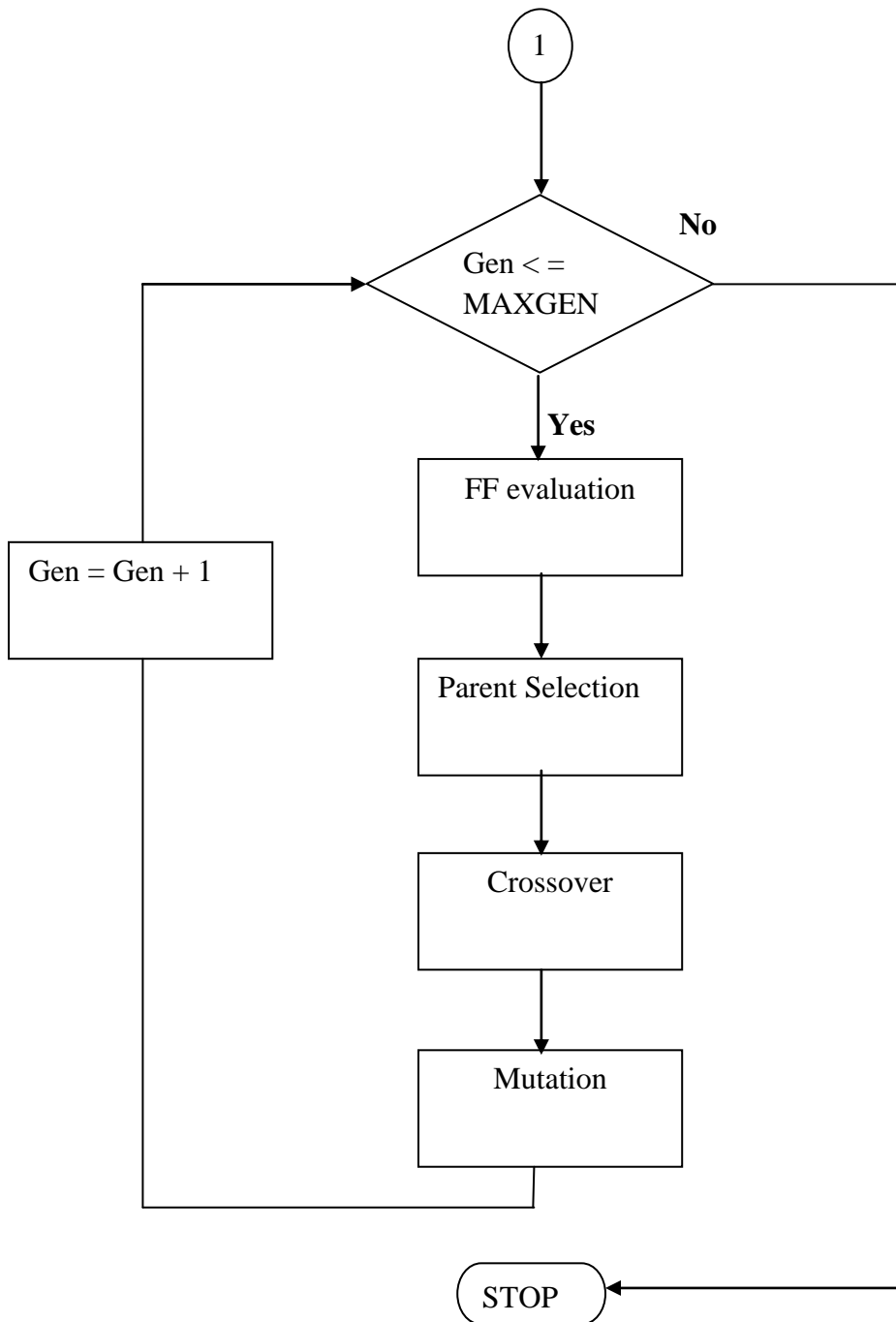


Fig 3.1: Flowchart of Simple Genetic Algorithm

The FF (fitness function) evaluation and genetic evolution take part in an iterative procedure, which ends when a maximum number of generations is reached, as shown in Fig.3.1.

SINGLE-OBJECTIVE OPF USING GA

4.1. SINGLE-OBJECTIVE OPF FORMULATION

OPF formulation for minimizing the fuel cost and fuel emissions (NO_x, CO_x and SO_x) to be used are as follows:

1) For Fuel Cost :

$$\text{Minimize } F_1 = \sum_{k=0}^n (a_{Fi} + b_{Fi}P_{Gi} + c_{Fi}P_{Gi}^2) \quad \$/\text{hr} \quad (4.1)$$

2) For NO_x emission :

$$\text{Minimize } F_2 = \sum_{k=0}^n (a_{Ni} + b_{Ni}P_{Gi} + c_{Ni}P_{Gi}^2) \quad \text{kg/hr} \quad (4.2)$$

3) For SO_x emission :

$$\text{Minimize } F_3 = \sum_{k=0}^n (a_{Si} + b_{Si}P_{Gi} + c_{Si}P_{Gi}^2) \quad \text{kg/hr} \quad (4.3)$$

4) For CO_x emission :

$$\text{Minimize } F_4 = \sum_{k=0}^n (a_{Ci} + b_{Ci}P_{Gi} + c_{Ci}P_{Gi}^2) \quad \text{kg/hr} \quad (4.4)$$

Now the objective functions corresponding to above are,

Subjected to,

$$h(P_{Gi}) = 0 \quad (4.5)$$

$$g(P_{Gi}) \leq 0 \quad (4.6)$$

here,

F_1, F_2, F_3 and F_4 are the total Fuel cost, NO_x, SO_x and CO_x emissions respectively.

a_{Fi}, b_{Fi}, c_{Fi} are the cost coefficients of i_{th} generator.

a_{Ni}, b_{Ni}, c_{Ni} are the NO_x emission coefficients of i_{th} generator.

a_{Si}, b_{Si}, c_{Si} are the SO_x emission coefficients of i_{th} generator.

a_{Ci}, b_{Ci}, c_{Ci} are the CO_x emission coefficients of i_{th} generator

4.2. GA BASED SINGLE OBJECTIVE OPF

In this GA based OPF is applied to IEEE-30 bus 6-generator test system. All the coding of proposed algorithm is developed in MATLAB 7.5.0 (R2007b) and run on the computer system with Core i3-370M Processor operating @ 2.40 GHz.

For minimizing each Objective Function using GAOPF the algorithm mentioned in Article 3.6. is to be followed.

4.2.1. MATLAB APPLICATION FOR OPF USING GA

1) **gaoptimset** :gaoptimset creates genetic algorithm options structure

Syntax:

gaoptimset

options = gaoptimset

options = gaoptimset (@ga)

options = gaoptimset (@gamultiobj)

options = gaoptimset ('param1',value1,'param2',value2,...)

Description:

options = gaoptimset (with no input arguments) creates a structure called options that contains the options, or parameters, for the genetic algorithm and sets parameters to [], indicating default values will be used.

options = gaoptimset(@ga) creates a structure called options that contains the default options for the genetic algorithm.

options = gaoptimset(@gamultiobj) creates a structure called options that contains the default options for gamultiobj.

options = gaoptimset('param1',value1,'param2',value2,...) creates a structure options and sets the value of 'param1' to value1, 'param2' to value2, and so on. Any unspecified parameters are set to their default values. It is sufficient to type only enough leading characters to define the parameter name uniquely. Case is ignored for parameter names.

2) Options: As the name suggests, it sets options with gaoptimset. Genetic Algorithm Options used in the program are as follows with complete description:

Population size: It gives the information regarding the size of the population. It has been taken as 50 in programming.

Display: it shows the level of display. For example 'off' | 'iter' | 'diagnose' | {'final'}. In this study 'iter' has been used.

Generations: Positive integer specifying the maximum number of iterations before the algorithm halts. 100 have been selected.

CrossoverFcn: Handle to the function that the algorithm uses to create crossover children
@crossoverheuristic { @crossoversscattered} @crossoverintermediate @crossoversinglepoint
@crossovertwopoint}.

PlotFcns: It plots the data computed by the algorithm, examples of few handles that can be used
are @gaplotbestf @gaplotbestindiv @gaplotdistance @gaplotexpectation @gaplotgeneology
@gaplotselection @gaplotrange @gaplotscorediversity etc. Out of these, @gaplotbestindiv and
@gaplotbestf have been used in programming.

Stall Generation Limit: The algorithm stops if there is no improvement in the objective function
for StallGenLimit consecutive generations. Its value is taken as 100.

Time Limit: The algorithm stops after running for TimeLimit seconds. Its value has been
selected as 300 sec.

Stall Time Limit: The algorithm stops if there is no improvement in the objective function for
StallTimeLimit seconds. Its value is taken as 300 sec.

3) Main function handles used in programming :

@Opf1 = This function handle is callable association to MATLAB function and is related to
generation cost of IEEE-30 bus system.

@opf3 = It is the function handle of NO_x emission related programming.

@opf4 = It is function handle for SO_x emission related programming.

@opf5 = This handle is related to CO_x emission related programming.

All these handles have been used in collaboration in the programming for calculating multi-
objective optimal power flow using GA.

4.3 RESULTS AND DISCUSSIONS

Finally the results for the GA based Single-Objective OPF after testing on IEEE-30 bus 6-generator test system using MATLAB environment have been obtained. The data used has been given in APPENDIX-I for IEEE 30 bus test system. The cost and emission coefficient data is given in APPENDIX-II. The single-line diagram of this system is shown in Fig. 4.1.

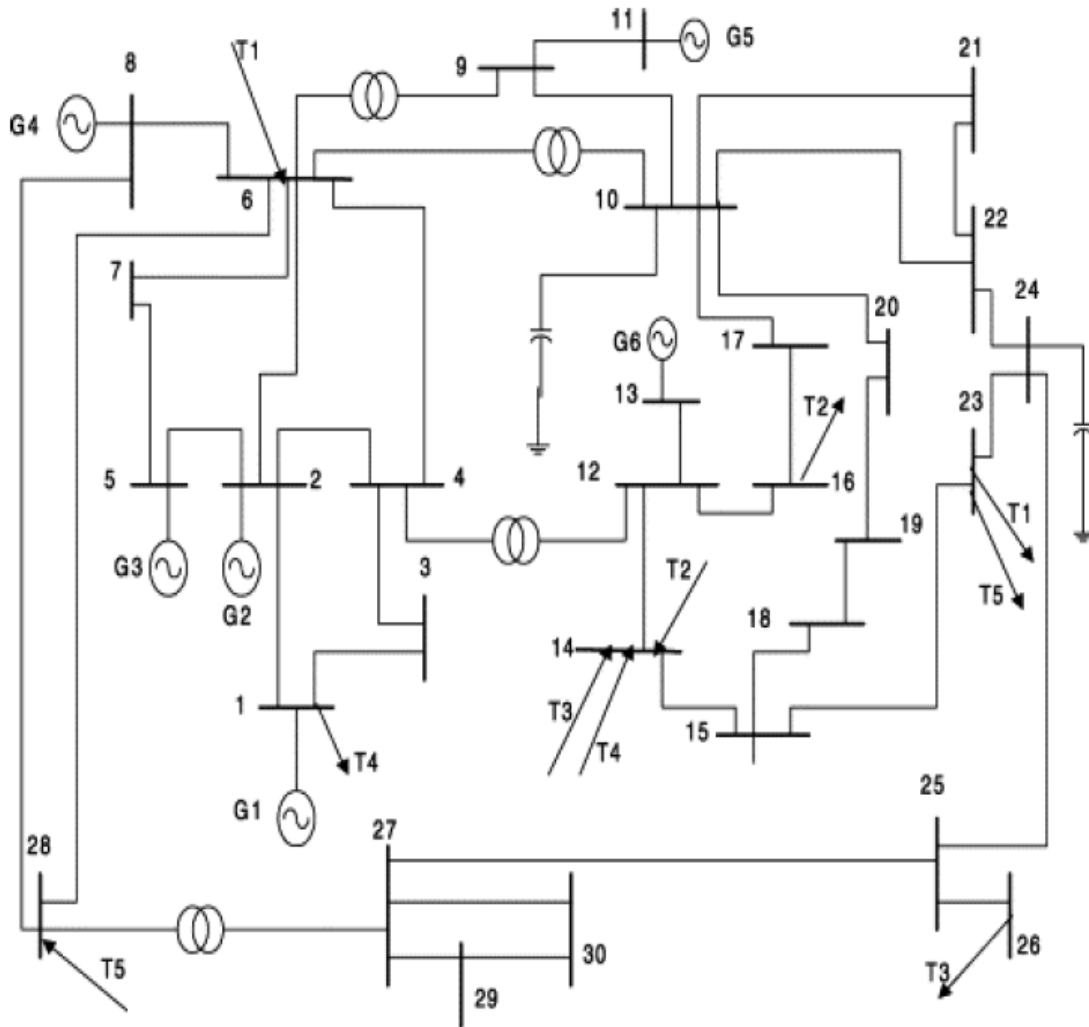


Fig 4.1: Single-line diagram of IEEE 30-bus 6-generator test system [25]

Following Objectives were optimised:

1) Minimization Of Fuel Cost

The coding results are obtained. The solutions after applying load flow using Newton Raphson as well as for GA based OPF are calculated and given in Table 4.1. Also the GA graph is shown in Fig 4.2. This graph is divided in two parts: one plotted between Fitness value and generation, and other plotted between Current best individual and Number of variables.

As the objective was minimization of Fuel cost , thus in Table 4.1 it is clear that after applying GA based OPF the Fuel cost has been reduced evidently to 770.0738 \$/hr which was 875.4458 \$/hr earlier while solving it by Load Flow using Newton-Raphson method.

In Fig 4.2 plot between Fitness value and generation, indicates that as the Generation increases, the curve is approaching towards minimum value of fitness function (Fuel cost). And the plot between Current best individual and Number of variables indicates the value of Current best individual for corresponding Generation.

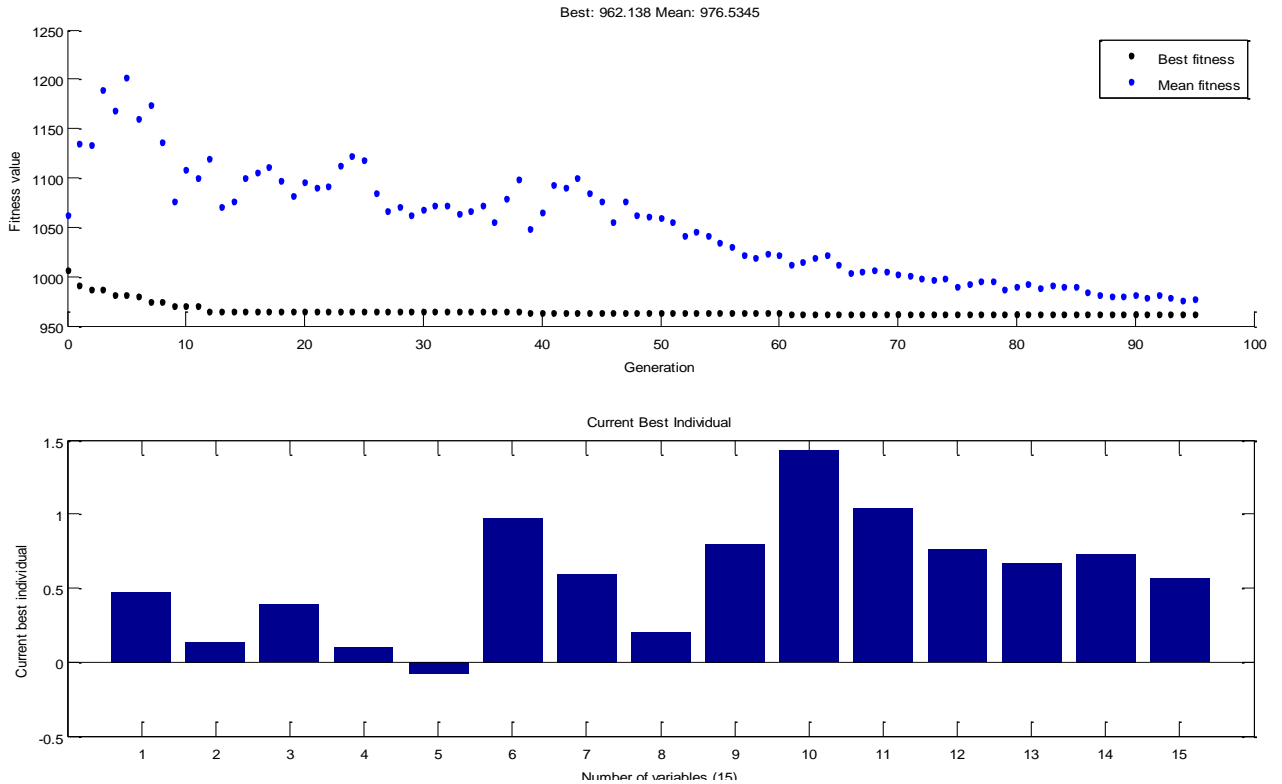


Fig 4.2: Cost minimization curve

Table 4.1: Comparison of OPF for minimizing Fuel cost

UNITS	IEEE- 30 BUS SYSTEM	
	SOLUTION AFTER LOAD FLOW (NEWTON-RAPHSON)	SOLUTION AFTER GAOPF
P_{G1}(in MW)	260.9980	174.4708
P_{G2}(in MW)	40.000	44.8131
P_{G5}(in MW)	0.00	17.7129
P_{G8}(in MW)	0.00	16.7050
P_{G11}(in MW)	0.00	16.6984
P_{G13}(in MW)	0.00	14.7806
Q_{G1}(in MVAR)	-17.021	111.7657
Q_{G2}(in MVAR)	48.822	-44.5879
Q_{G5}(in MVAR)	35.975	15.8003
Q_{G8}(in MVAR)	30.826	32.1640
Q_{G11}(in MVAR)	16.119	-10.5155
Q_{G13}(in MVAR)	10.423	-1.6852
Fuel Cost (\$/hr)	875.4458	777.4574
Transmission Loss(in MW)	17.599	9.27792
NO_x emission (in Kg/hr)	1728.484	1434.502
SO_x emission (in Kg/hr)	3107.864	2940.249
CO_x emission (in Kg/hr)	25950.64	18990.23

The best optimal solution for minimization of fuel cost gives minimum value of fuel cost = 777.4574 \$/hr where values of P_{G1}, P_{G2}, P_{G5}, P_{G8}, P_{G11}, P_{G13}, Q_{G1}, Q_{G2}, Q_{G5}, Q_{G8}, Q_{G11} and Q_{G13} are mentioned in above Table 4.1.

2) Minimization of NO_x Fuel emission

The solutions after applying load flow using Newton Raphson as well as for GA based OPF are calculated for single-objective NO_x fuel emission and is given in Table 4.2 and the GA graph is shown in Fig 4.3.

In Fig 4.3 plot between Fitness value and generation, indicates that as the Generation increases, the curve is approaching towards minimum value of fitness function (Fuel emission NO_x). And the plot between Current best individual and Number of variables, indicate the value of Current best individual for corresponding Generation.

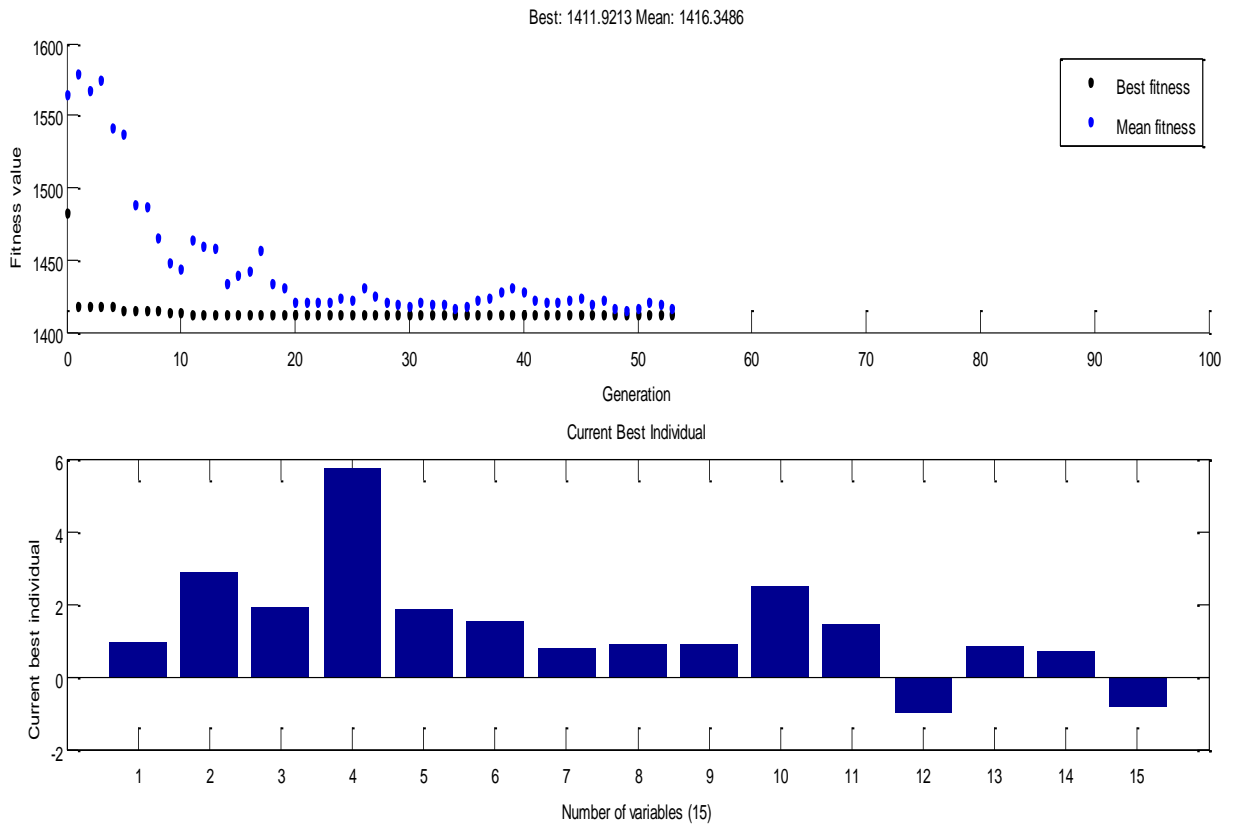


Fig 4.3: NO_x emission minimization curve

Table 4.2: Comparison of OPF for minimizing NO_x emissions

UNITS	IEEE- 30 BUS SYSTEM	
	SOLUTION AFTER LOAD FLOW (NEWTON-RAPHSON)	SOLUTION AFTER GAOFF
P_{G1}(in MW)	260.9980	52.0818
P_{G2}(in MW)	40.000	80.000
P_{G5}(in MW)	0.00	50.000
P_{G8}(in MW)	0.00	35.000
P_{G11}(in MW)	0.00	30.000
P_{G13}(in MW)	0.00	37.0753
Q_{G1}(in MVAR)	-17.021	123.1414
Q_{G2}(in MVAR)	48.822	-144.6652
Q_{G5}(in MVAR)	35.975	48.4393
Q_{G8}(in MVAR)	30.826	83.7299
Q_{G11}(in MVAR)	16.119	-39.4434
Q_{G13}(in MVAR)	10.423	-2.2509
Fuel Cost (\$/hr)	875.4458	954.5934
Transmission Loss(in MW)	17.599	4.62863
NO_x emission (in Kg/hr)	1728.484	1214.299
SO_x emission (in Kg/hr)	3107.864	2823.347
CO_x emission (in Kg/hr)	25950.64	16144.76

Thus, best optimal solution for minimization of NO_x gives minimum value of NO_x emission=1214.299Kg/hr where values of P_{G1}, P_{G2}, P_{G5}, P_{G8}, P_{G11}, P_{G13}, Q_{G1}, Q_{G2}, Q_{G5}, Q_{G8}, Q_{G11} and Q_{G13} are mentioned in above Table 4.2.

3) Minimization of SO_x Fuel emission

The solutions after applying load flow using Newton Raphson as well as for GA based OPF are calculated for single-objective SO_x fuel emission and is given in Table 4.3 and the GA graph is shown in Fig 4.4

In Fig 4.4, plot between Fitness value and generation, indicates that as the Generation increases, the curve is approaching towards minimum value of fitness function (Fuel emission SO_x). And the plot between Current best individual and Number of variables, indicate the value of Current best individual for corresponding Generation.

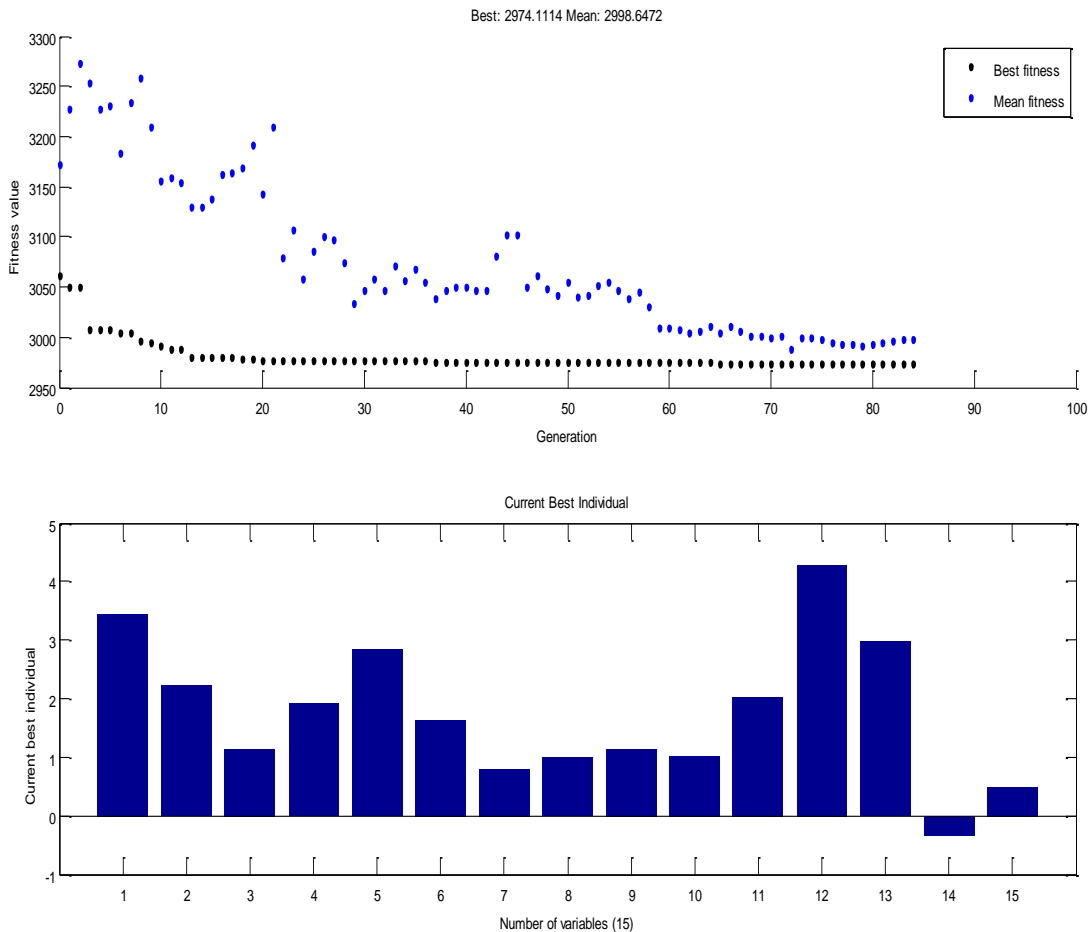


Fig 4.4: SO_x emission minimization curve

Table 4.3: Comparison of OPF for minimizing SO_x emissions

UNITS	IEEE- 30 BUS SYSTEM	
	Solution after Load Flow (Newton-Raphson)	Solution after GAOPF
P_{G1}(in MW)	260.9980	66.9280
P_{G2}(in MW)	40.000	76.6001
P_{G5}(in MW)	0.00	49.0638
P_{G8}(in MW)	0.00	22.1501
P_{G11}(in MW)	0.00	23.2766
P_{G13}(in MW)	0.00	40.000
Q_{G1}(in MVAR)	-17.021	58.9997
Q_{G2}(in MVAR)	48.822	-19.0940
Q_{G5}(in MVAR)	35.975	-1.3980
Q_{G8}(in MVAR)	30.826	38.9903
Q_{G11}(in MVAR)	16.119	26.2718
Q_{G13}(in MVAR)	10.423	-13.3068
Fuel Cost (\$/hr)	875.4458	906.3385
Transmission Loss(in MW)	17.599	5.10425
NO_x emission (in Kg/hr)	1728.484	1254.173
SO_x emission (in Kg/hr)	3107.864	2800.571
CO_x emission (in Kg/hr)	25950.64	15579.57

Thus, best optimal solution for minimization of SO_x gives minimum value of SO_x emission=2800.571 Kg/hr corresponding to values of P_{G1}, P_{G2}, P_{G5}, P_{G8}, P_{G11}, P_{G13}, Q_{G1}, Q_{G2}, Q_{G5}, Q_{G8}, Q_{G11} and Q_{G13} are mentioned in above Table 4.3.

4) Minimization of CO_x Fuel emission

The solutions after applying load flow using Newton Raphson as well as for GA based OPF are calculated for single-objective CO_x fuel emission and is given in Table 4.4 and the GA graph is shown in Fig 4.5.

In Fig 4.5 plot between Fitness value and generation, indicates that as the Generation increases, the curve is approaching towards minimum value of fitness function (Fuel emission CO_x). And the plot between Current best individual and Number of variables, indicate the value of Current best individual for corresponding Generation.

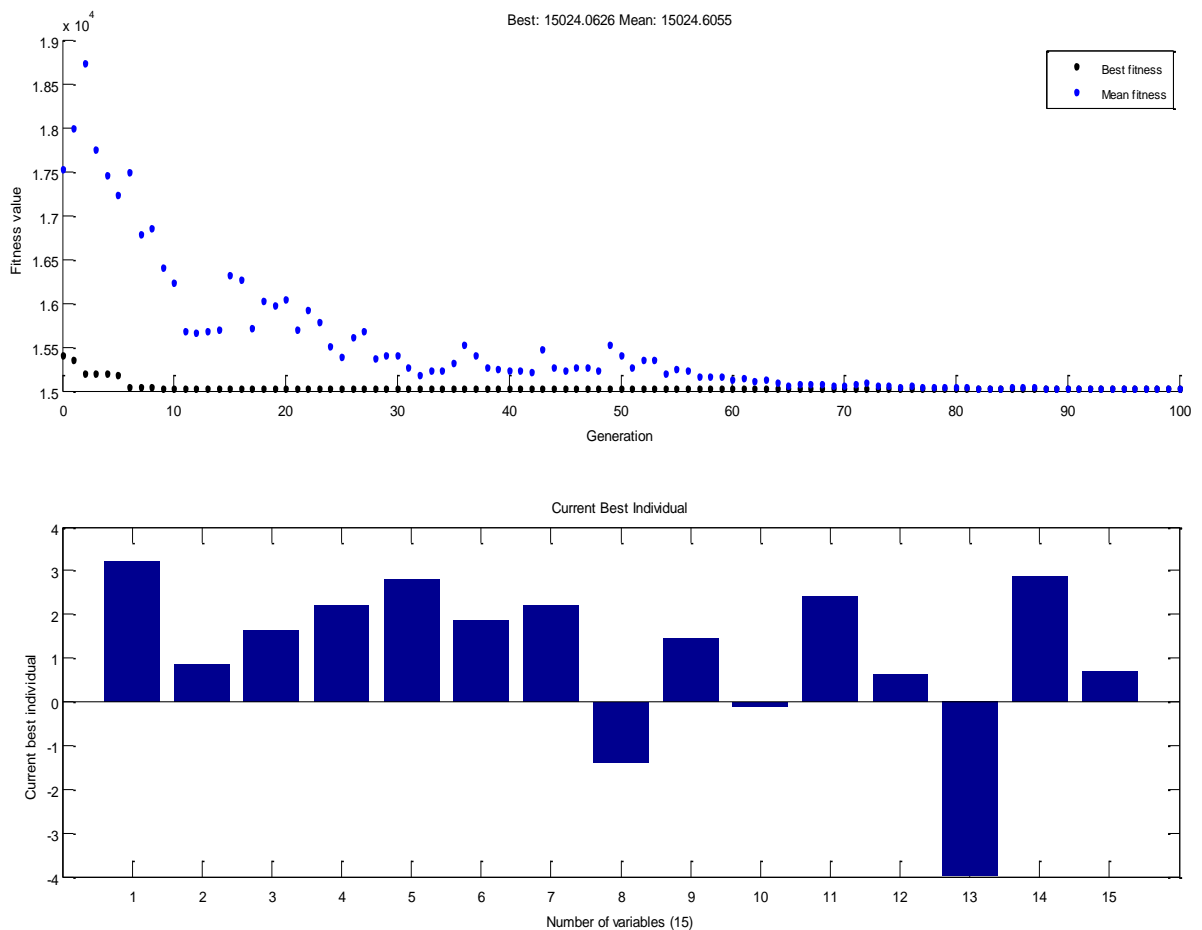


Fig 4.5: CO_x emission minimization curve

Table 4.4: Comparison of OPF for minimizing CO_x emissions

UNITS	IEEE- 30 BUS SYSTEM	
	SOLUTION AFTER LOAD FLOW (NEWTON-RAPHSON)	SOLUTION AFTER GAOPF
P_{G1}(in MW)	260.9980	100.0866
P_{G2}(in MW)	40.000	80.00
P_{G5}(in MW)	0.00	24.0084
P_{G8}(in MW)	0.00	32.7622
P_{G11}(in MW)	0.00	23.1506
P_{G13}(in MW)	0.00	40
Q_{G1}(in MVAR)	-17.021	176.5583
Q_{G2}(in MVAR)	48.822	-272.1136
Q_{G5}(in MVAR)	35.975	170.3245
Q_{G8}(in MVAR)	30.826	45.0107
Q_{G11}(in MVAR)	16.119	-33.3682
Q_{G13}(in MVAR)	10.423	56.6903
Fuel Cost (\$/hr)	875.4458	908.0072
Transmission Loss(in MW)	17.599	6.56183
NO_x emission (in Kg/hr)	1728.484	1284.206
SO_x emission (in Kg/hr)	3107.864	2929.418
CO_x emission (in Kg/hr)	25950.64	14970.00

Thus, best optimal solution for minimization of CO_x gives minimum value of CO_x emission=14970 Kg/hr where values of P_{G1}, P_{G2}, P_{G5}, P_{G8}, P_{G11}, P_{G13}, Q_{G1}, Q_{G2}, Q_{G5}, Q_{G8}, Q_{G11} and Q_{G13} are mentioned in above Table 4.4.

CHAPTER-5

MULTIOBJECTIVE OPF USING GA

5.1 INTRODUCTION

Many engineering problems have multiple objectives, including engineering system design and reliability optimization. There have been several interesting and successful implementations of multi-objective GA for this class of problems [26]. In response to public awareness of the environmental situation, many engineers came up with new methods to reduce air pollution keeping it economical as well. Therefore lot of research work is being done to handle such conflicting situations through multi-objective optimization [27].

As these problems involve simultaneous optimization of several objective functions, therefore, generally these functions are conflicting objectives. These conflicting objective functions gives rise to a set of optimal solutions instead of one optimal solution. The reason for the optimality of many solutions is that no one can be considered to be better than any other with respect to all objective functions. These optimal solutions are known as Pareto-optimal solutions.

A general multi-objective optimization problem consists of a number of objectives to be optimized simultaneously and is associated with a number of equality and inequality constraints [28].

The aim of multi-objective optimization is to help engineers (or decision makers) take the right decision in conflicting situations with several objectives to be satisfied simultaneously. Further for large-scale integrated electric power systems, there is no other alternative but to use the digital computer as a computation tool for fast, accurate and robust solution procedures.

The objective function can be of minimization or maximization type. In multi objective optimization finding an optimal solution by considering all the objectives is very essential. The multi-objective problem can be formulated as:

$$\text{Min/Max } F(x) = [f_1(x), f_2(x), f_3(x), f_4(x) \dots f_n(x)] \quad (5.1)$$

Subjected to,

$$g_i(x) \leq 0 \quad ; i = 1, 2, 3, 4, \dots, i \quad (5.2)$$

$$h_j(x) = 0 \quad ; j = 1, 2, 3, 4, \dots, j \quad (5.3)$$

where $f_1(x), f_2(x), f_3(x), f_4(x), \dots, f_n(x)$ denotes objective functions.

Most multi-objective meta-heuristics [29] and [30] (Meta-heuristics methods include: genetic algorithms, ant colony optimization, simulated annealing, scatter search, etc.) have been derived from their single-objective counterparts using three different approaches namely weighted sum of objectives, alternate objectives, and Pareto ranking. In weighted sum of objectives approach [31], a weight w_i is assigned to each normalized objective function $f_n(x)$ so that problem is converted into a single objective problem with a scalar objective function as follows:

$$\text{Min } z = w_1F_1(x) + w_2F_2(x) + \dots + w_nF_n(x) \quad (5.4)$$

where

$$n = 1, 2, 3, 4, \dots, n \quad (5.5)$$

The weighted sum approach is straight-forward and easy to implement. For multiple solutions, the problem must be solved multiple times with different weight combinations. But the main problem with this method is selecting a weight vector in each run. A single objective function is randomly selected in each iteration to evaluate candidate solutions in the selection of new current solutions. This is achieved by using GA.

5.2 MATLAB APPLICATION FOR MULTI-OBJECTIVE OPTIMIZATION USING GA

gamultiobj: Find minima of multiple functions using genetic algorithm.

Syntax and Description:

gamultiobj implements the genetic algorithm at the command line to minimize a multi-component objective function.

X = gamultiobj (FITNESSFCN, NVAR) finds a local Pareto set X of the objective functions defined in FITNESSFCN. NVAR is the dimension of the optimization problem (number of decision variables). FITNESSFCN accepts a vector X of size 1-by-NVAR and returns a vector of size 1-by-numberOfObjectives evaluated at a decision variable. X is a matrix with NVAR columns. The number of rows in X is the same as the number of Pareto solutions. All solutions in a Pareto set are equally optimal; it is up to the designer to select a solution in the Pareto set depending on the application.

X = gamultiobj (FITNESSFCN, NVAR, A, b) finds a local Pareto set X of the objective functions defined in FITNESSFCN, subject to the linear inequalities. Linear constraints are supported only for the default Population Type option ('double Vector'). Other population types, e.g., 'bitString' and 'custom', are not supported.

X = gamultiobj(FITNESSFCN, NVAR, A, b, Aeq, beq) finds a local Pareto set X of the objective functions defined in FITNESSFCN, subject to the linear equalities as well as the linear inequalities. (Set A=[] and b=[] if no inequalities exist.) Linear constraints are supported only for the default Population Type option ('double Vector'). Other population types, e.g., 'bitString' and 'custom', are not supported.

X = gamultiobj(FITNESSFCN, NVAR, A, b, Aeq, beq, LB, UB) defines a set of lower and upper bounds on the design variables X so that a local Pareto set is found in the range . Use empty matrices for LB and UB if no bounds exist. Set LB(i) = -Inf if X(i) is unbounded below; set UB(i) = Inf if X(i) is unbounded above. Bound constraints are supported only for the default PopulationType option ('doubleVector'). Other population types, e.g., 'bitString' and 'custom', are not supported.

X = gamultiobj (FITNESSFCN, NVARs, A, b, Aeq, beq, LB, UB, options) finds a Pareto set X with the default optimization parameters replaced by values in the structure options. Options can be created with the gaoptimset function.

X = gamultiobj (problem) finds the Pareto set for problem, where problem is a structure containing the following fields:

Table 5.1 various fields in gamultiobj (problem)

Fitnessfcn	Fitness functions
Nvars	Number of design variables
Aineq	A matrix for linear inequality constraints
Bineq	b vector for linear inequality constraints
Aeq	A matrix for linear equality constraints
Beq	b vector for linear equality constraints
Lb	Lower bound on x
Ub	Upper bound on x
Options	Options structure created using gaoptimset

5.3 ALGORITHM

Step 1: Feed the database of IEEE-30 bus system data i.e. generator data, bus data, line data, transformer data and capacitor/reactor data.

Step 2: Assume suitably maximum number of generations or populations and population size.

Step 3: Put value of population counter = 0

Step 4: Randomly generate chromosomes.

Step 5: Using Newton-Raphson method, run power flow. Then calculate power flow in each transmission line and slack bus generation, voltage magnitude and phase angles for all the buses.

Step 6: Now check whether any constraint (voltage magnitude, phase angle and reactive power at all generator buses) is violating its limit or not. If violation occurs then for generating fresh values go to step 4.

Step 7: If all constraints are within limits then accept these values and increment the population counter by 1. If the population is less or equals to population size then again go to Step 4.

Step 8: Randomly generate weights i.e. w_1 , w_2 , w_3 and w_4 .

Step 9: Now check whether weight constraint is violating its limit or not. If violation occurs then again go to Step 8 for generating new values of weights.

Step 10: Calculate the fitness considering cost of generation, total NO_x , CO_x and SO_x emissions with different weightage for each set of chromosomes and then store it.

Step 11: Now from previous step's data, choose the best fitness.

Step 12: Apply crossover operator to it.

Step 13: Again run power flow for each set of new generated pattern.

Step 14: Then again check the constraints as done in step 6.

Step 15: If any constraint is not satisfied then reject the new generation pattern. But if it satisfies then proceed to next step.

Step 16: Apply mutation operator on selected generated pattern.

Step 17: On this mutated pattern again run power flow using Newton-Raphson and hence check constraints as in step 6.

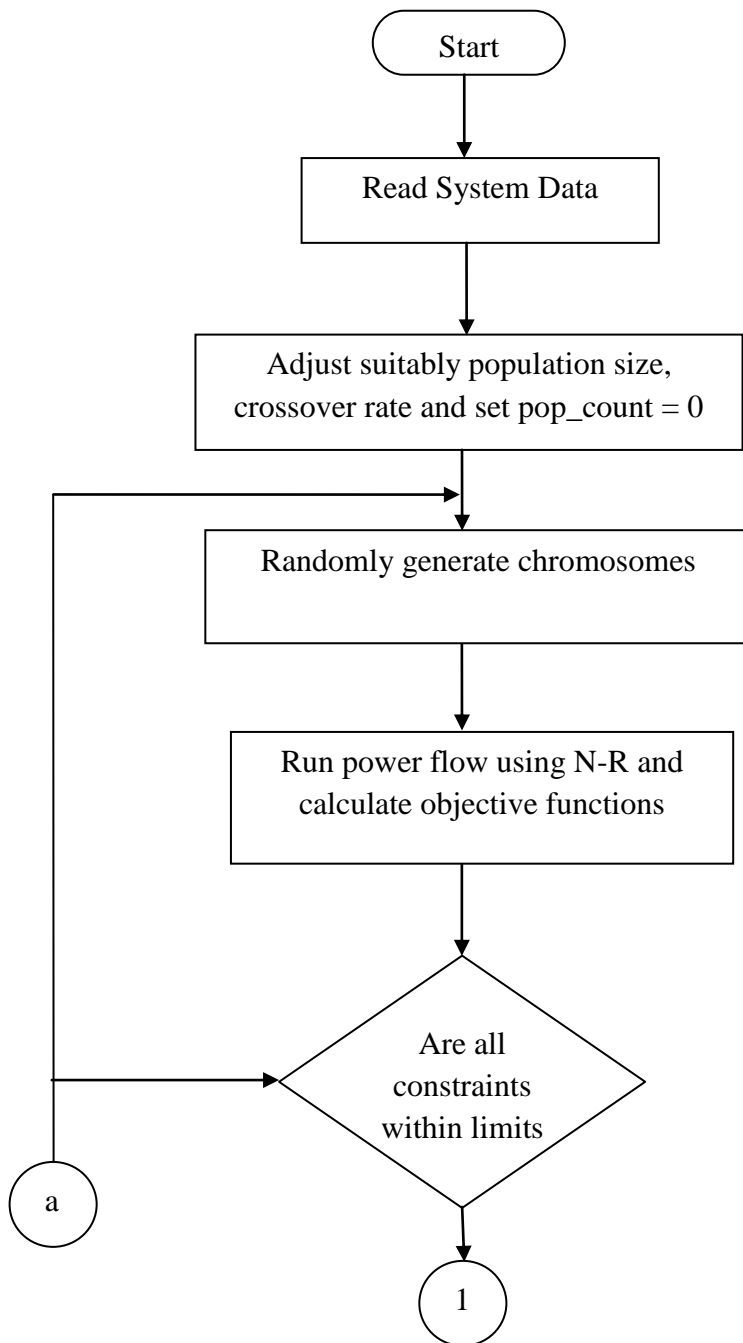
Step 18: If constraints are satisfied proceed onto next step otherwise go back to step 4.

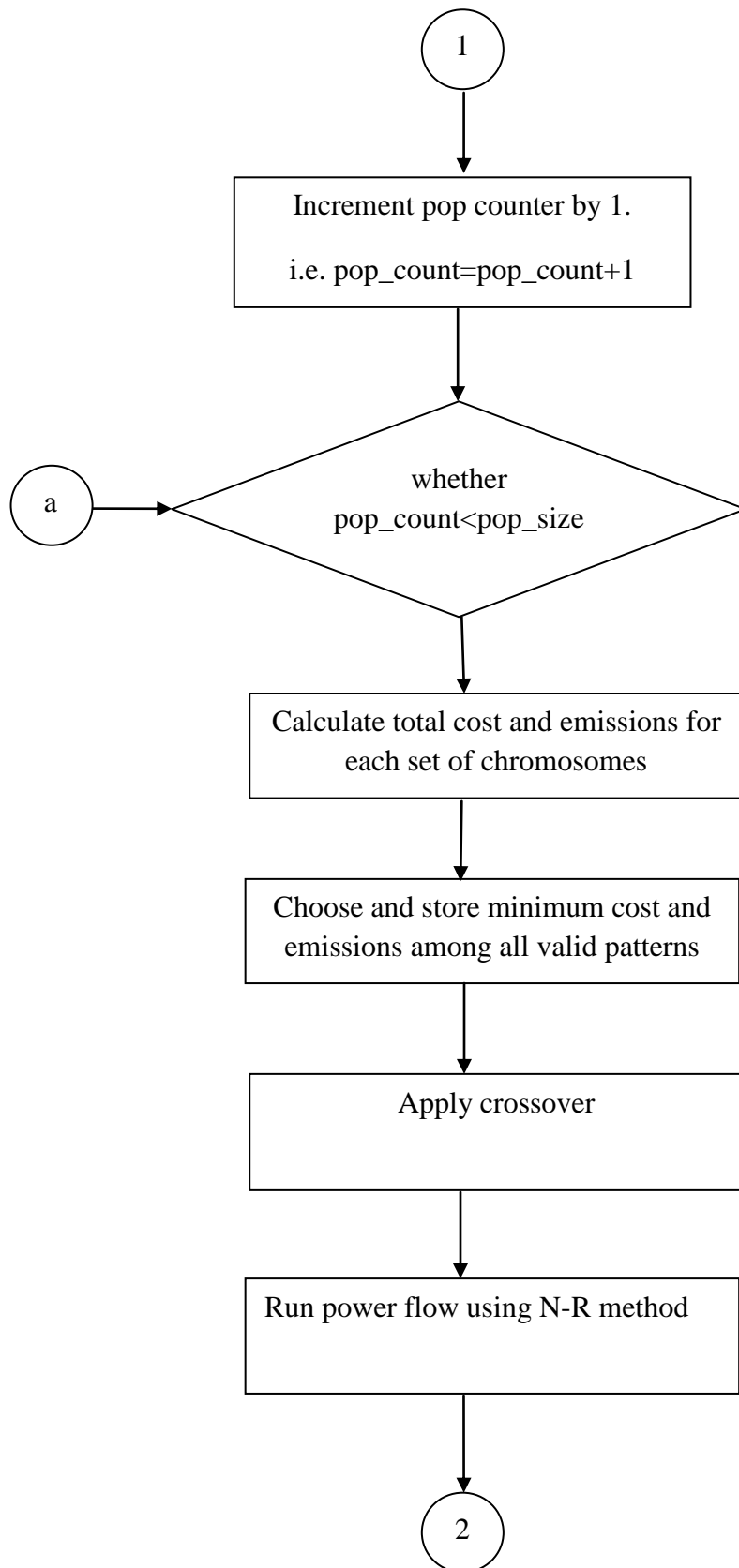
Step 19: Calculate F. Where $F = w_1 * F_1 + w_2 * F_2 + w_3 * F_3 + w_4 * F_4$.

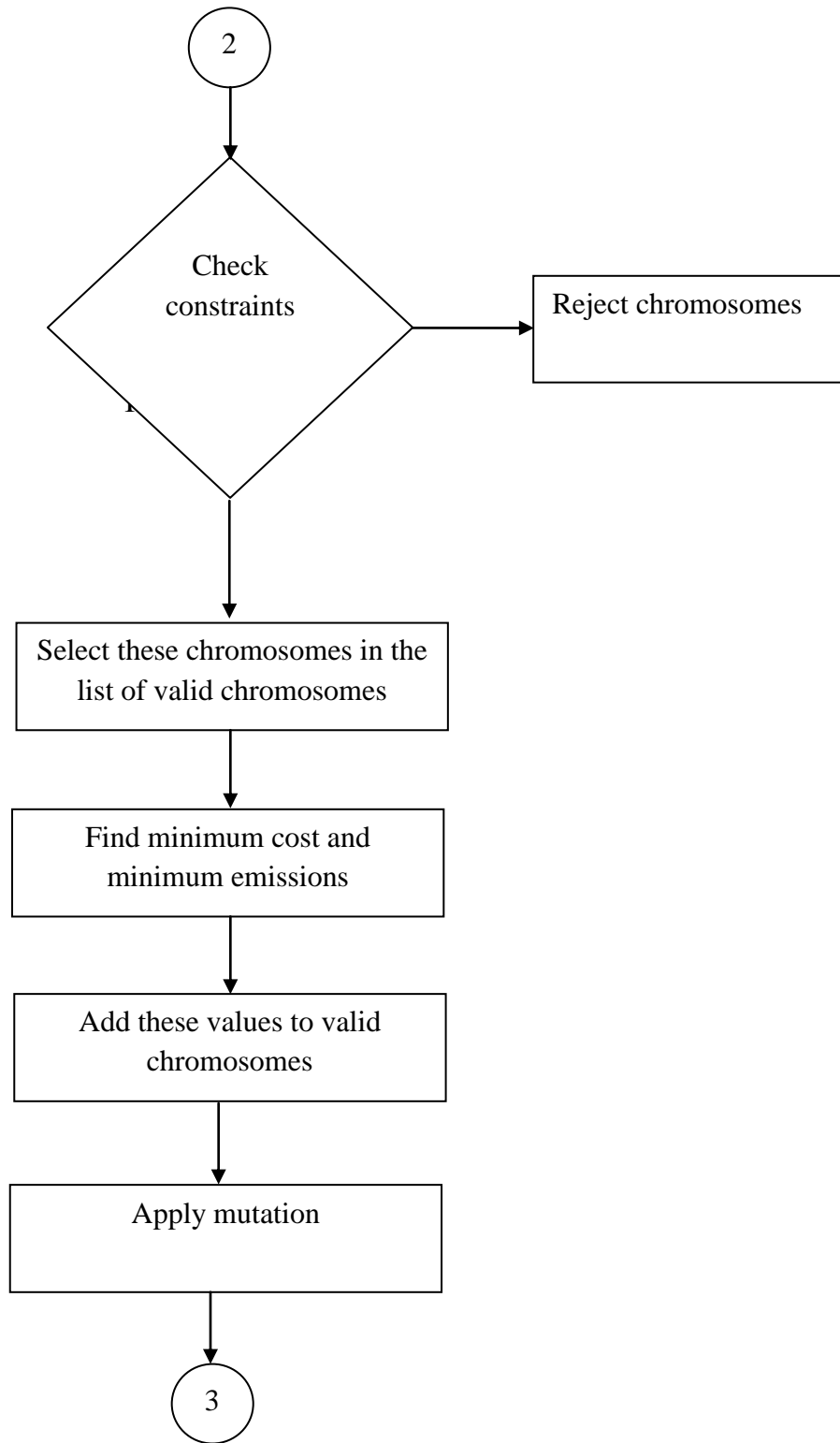
Step 20: Calculate fitness corresponding to each value of F.

Step 21: Finally choose the optimum solution by choosing the one having minimum fitness.

5.4 FLOWCHART







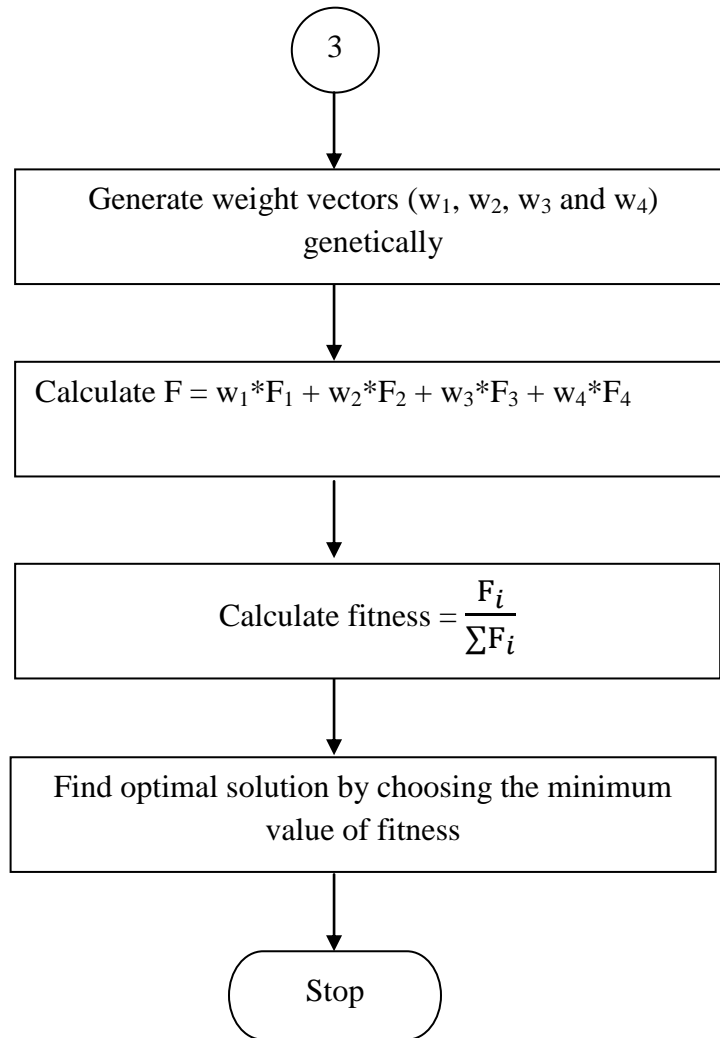


Fig 5.1 Flowchart of Multi-objective OPF using GA

5.5 RESULTS AND DISCUSSIONS

The results have been obtained from proposed algorithm for Multi-objective GA based OPF and has been tested on IEEE 30-bus 6-generator system. All the coding of proposed algorithm is developed in MATLAB 7.10.0 (R2010a) and run on the computer system with Core i3-370M Processor operating @ 2.40 GHz.

Different combinations of objectives and weights have been used for Multi-objective OPF considering four objectives:

- Fuel cost, F_1 (in \$/hr)

- NO_x Emissions, F₂ (in Kg/hr)
- CO_x Emissions, F₃ (in Kg/hr)
- SO_x Emissions, F₄ (in Kg/hr)

Above four objectives are included in following multi-objective optimization problem:

$$F = w_1 * F_1 + w_2 * F_2 + w_3 * F_3 + w_4 * F_4$$

where

F₁, F₂, F₃ and F₄ are calculated using Eqs. 4.1-4.6

Hundred trials have been run. On the basis of these trials fitness has been calculated by using following mathematical expression:

$$\text{Fitness} = \frac{Fi}{\sum_{i=1}^{20} Fi}$$

where

i = population generation trial

In order to decide the best solution out of these fitnesses, the population generation trial corresponding to minimum fitness, is chosen. Finally that solution is considered as best optimal solution. In this case solution corresponding to population generation trial 87 has been accepted as optimal solution as shown in Table 5.2. Corresponding to these solutions, the real powers and reactive power generations on six generators is given in Table 5.3 and Table 5.4 respectively. That is, the best optimal solution corresponds to:

$$w_1 = 0.330414, w_2 = 0.335195, w_3 = 0.298175, w_4 = 0.036216;$$

$$F_1 = 883\$/hr, F_2 = 1363kg/hr, F_3 = 3053kg/hr, F_4 = 18151kg/hr;$$

$$F = 2316.31$$

$$\text{Fitness} = 0.0026107$$

$$P_{G1} = 161.766MW, P_{G2} = 49.2264MW, P_{G5} = 30.4824MW, P_{G8} = 30.8201MW, P_{G11} = 20.8378MW, P_{G13} = 17.0973MW;$$

$$Q_{G1} = -134.65MVAR, Q_{G2} = 112.887MVAR, Q_{G5} = 37.8683MVAR, Q_{G8} = 47.3033MVAR,$$

$$Q_{G11} = 28.3829MVAR, Q_{G13} = -2.0991MVAR;$$

$$\text{Losses} = 12.7118MW$$

Table 5.2 Fitness values corresponding to solutions of multi-objective OPF problem

trial	w₁	w₂	w₃	w₄	F₁	F₂	F₃	F₄	F	fitness
1	0.7	0.1	0.1	0.1	892	1370	3027	15727	2636.8	0.0029719
2	0.6	0.1	0.1	0.2	844	1425	3007	17164	4382.4	0.0049394
3	0.5	0.2	0.2	0.1	805	1345	2913	17085	2962.6	0.0033391
4	0.5	0.1	0.1	0.3	895	1295	2974	15583	5549.3	0.0062546
5	0.4	0.2	0.3	0.1	888	1334	2993	16513	3171.2	0.0035743
6	0.4	0.1	0.2	0.3	864	1265	2884	17251	6224.2	0.0070153
7	0.3	0.5	0.1	0.1	858	1410	3001	17569	3019.4	0.0034032
8	0.3	0.2	0.4	0.1	873	1404	3063	18837	3651.6	0.0041157
9	0.2	0.3	0.2	0.3	870	1393	3003	17326	6390.3	0.0072025
10	0.2	0.4	0.3	0.1	876	1371	3000	18840	3507.6	0.0039534
11	0.1	0.2	0.3	0.4	859	1411	2989	19055	8886.8	0.0100163
12	0.1	0.1	0.6	0.2	898	1348	3025	17495	5538.6	0.0062425
13	0.6	0.2	0.1	0.1	830	1345	2900	15525	2609.5	0.0029412
14	0.6	0.1	0.2	0.1	910	1293	2907	15639	2820.6	0.0031791
15	0.031201	0.09537	0.031201	0.842227	875	1386	3029	16876	14467.4	0.0163062
16	0.061304	0.109607	0.055281	0.773808	833	1430	3003	18046	14338	0.0161603
17	0.003759	0.060483	0.009571	0.926187	846	1313	2908	15457	14426.5	0.0162601
18	0.138847	0.180481	0.12731	0.553362	938	1360	3022	16237	9745.36	0.010984
19	0.293406	0.312219	0.251214	0.143161	859	1321	2892	16071	3691.73	0.0041609
20	0.040681	0.086736	0.158219	0.714364	869	1412	2986	17173	12898	0.0145374
21	0.051243	0.265911	0.004063	0.678783	873	1390	3010	15953	11255.2	0.0126857
22	0.061905	0.105451	0.13249	0.700154	942	1372	3079	18320	13437.8	0.0151457
23	0.031164	0.14853	0.077046	0.74326	906	1342	2980	15857	12243	0.0137991

24	0.06149	0.005899	0.150834	0.781777	911	1333	2996	15953	12987.5	0.0146382
25	0.23663	0.274936	0.212571	0.275863	893	1423	3088	18457	6350.57	0.0071577
26	0.225997	0.159792	0.221633	0.392578	906	1399	3060	16464	7569.9	0.008532
27	0.086843	0.128699	0.059311	0.725148	837	1319	2928	16670	12504.3	0.0140936
28	0.212119	0.27214	0.27269	0.243051	840	1323	2918	18083	5729.02	0.0064572
29	0.18711	0.059429	0.184566	0.568896	842	1357	2961	17822	10923.6	0.0123119
30	0.207196	0.077647	0.179682	0.535475	831	1311	2854	16016	9362.95	0.010553
31	0.138847	0.180481	0.12731	0.553362	938	1360	3022	16237	9745.36	0.010984
32	0.293406	0.312219	0.251214	0.143161	859	1321	2892	16071	3691.73	0.0041609
33	0.040681	0.086736	0.158219	0.714364	869	1412	2986	17173	12898	0.0145374
34	0.051243	0.265911	0.004063	0.678783	873	1390	3010	15953	11255.2	0.0126857
35	0.061905	0.105451	0.13249	0.700154	942	1372	3079	18320	13437.8	0.0151457
36	0.031164	0.14853	0.077046	0.74326	906	1342	2980	15857	12243	0.0137991
37	0.06149	0.005899	0.150834	0.781777	911	1333	2996	15953	12987.5	0.0146382
38	0.23663	0.274936	0.212571	0.275863	893	1423	3088	18457	6350.57	0.0071577
39	0.225997	0.159792	0.221633	0.392578	906	1399	3060	16464	7569.9	0.008532
40	0.086843	0.128699	0.059311	0.725148	837	1319	2928	16670	12504.3	0.0140936
41	0.300899	0.0502	0.28653	0.36237	835	1369	2921	18234	7764.38	0.0087512
42	0.413016	0.00998	0.367169	0.209835	838	1404	2985	17483	5124.66	0.005776
43	0.090074	0.127616	0.081447	0.700864	833	1319	2920	17823	12972.7	0.0146215
44	0.061905	0.105451	0.13249	0.700154	942	1372	3079	18320	13437.8	0.0151457
45	0.031164	0.14853	0.077046	0.74326	906	1342	2980	15857	12243	0.0137991
46	0.06149	0.005899	0.150834	0.781777	911	1333	2996	15953	12987.5	0.0146382
47	0.23663	0.274936	0.212571	0.275863	893	1423	3088	18457	6350.57	0.0071577
48	0.225997	0.159792	0.221633	0.392578	906	1399	3060	16464	7569.9	0.008532
49	0.086843	0.128699	0.059311	0.725148	837	1319	2928	16670	12504.3	0.0140936

50	0.031164	0.14853	0.077046	0.74326	906	1342	2980	15857	12243	0.0137991
51	0.06149	0.005899	0.150834	0.781777	911	1333	2996	15953	12987.5	0.0146382
52	0.23663	0.274936	0.212571	0.275863	893	1423	3088	18457	6350.57	0.0071577
53	0.225997	0.159792	0.221633	0.392578	906	1399	3060	16464	7569.9	0.008532
54	0.086843	0.128699	0.059311	0.725148	837	1319	2928	16670	12504.3	0.0140936
55	0.212119	0.27214	0.27269	0.243051	840	1323	2918	18083	5729.02	0.0064572
56	0.298482	0.253792	0.254024	0.193701	869	1422	2995	19562	5170.26	0.0058274
57	0.163531	0.198292	0.162225	0.475953	865	1293	2881	16838	8879.31	0.0100079
58	0.040681	0.086736	0.158219	0.714364	869	1412	2986	17173	12898	0.0145374
59	0.051243	0.265911	0.004063	0.678783	873	1390	3010	15953	11255.2	0.0126857
60	0.061905	0.105451	0.13249	0.700154	942	1372	3079	18320	13437.8	0.0151457
61	0.06149	0.005899	0.150834	0.781777	911	1333	2996	15953	12987.5	0.0146382
62	0.23663	0.274936	0.212571	0.275863	893	1423	3088	18457	6350.57	0.0071577
63	0.225997	0.159792	0.221633	0.392578	906	1399	3060	16464	7569.9	0.008532
64	0.307349	0.204468	0.290856	0.197327	882	1470	3092	18837	5188.03	0.0058474
65	0.123537	0.131085	0.122603	0.622776	937	1390	3095	16691	11072.2	0.0124794
66	0.114915	0.153792	0.106499	0.624794	892	1307	2993	15909	10562.1	0.0119045
67	0.216478	0.223273	0.203277	0.356973	891	1313	2921	15221	6513.3	0.0073411
68	0.241231	0.295674	0.244694	0.218401	858	1396	2967	16977	5053.54	0.0056958
69	0.22953	0.290275	0.279537	0.200658	901	1315	2999	15433	4523.6	0.0050985
70	0.336782	0.069383	0.31345	0.280386	890	1336	2959	15836	5760.12	0.0064922
71	0.06149	0.005899	0.150834	0.781777	911	1333	2996	15953	12987.5	0.0146382
72	0.306878	0.070113	0.302431	0.320578	839	1385	2984	18189	7088.02	0.0079889
73	0.422941	0.021875	0.420593	0.13459	856	1488	3049	19790	4340.51	0.0048922
74	0.041378	0.180479	0.013447	0.764696	901	1458	3125	20122	15729.7	0.0177289
75	0.300899	0.0502	0.28653	0.36237	835	1369	2921	18234	7764.38	0.0087512

76	0.413016	0.00998	0.367169	0.209835	838	1404	2985	17483	5124.66	0.005776
77	0.090074	0.127616	0.081447	0.700864	833	1319	2920	17823	12972.7	0.0146215
78	0.061905	0.105451	0.13249	0.700154	942	1372	3079	18320	13437.8	0.0151457
79	0.031164	0.14853	0.077046	0.74326	906	1342	2980	15857	12243	0.0137991
80	0.086843	0.128699	0.059311	0.725148	837	1319	2928	16670	12504.3	0.0140936
81	0.212119	0.27214	0.27269	0.243051	840	1323	2918	18083	5729.02	0.0064572
82	0.123537	0.131085	0.122603	0.622776	937	1390	3095	16691	11072.2	0.0124794
83	0.114915	0.153792	0.106499	0.624794	892	1307	2993	15909	10562.1	0.0119045
84	0.216478	0.223273	0.203277	0.356973	891	1313	2921	15221	6513.3	0.0073411
85	0.22953	0.290275	0.279537	0.200658	901	1315	2999	15433	4523.6	0.0050985
86	0.336782	0.069383	0.31345	0.280386	890	1336	2959	15836	5760.12	0.0064922
87	0.330414	0.335195	0.298175	0.036216	883	1363	3053	18151	2316.31	0.0026107
88	0.086843	0.128699	0.059311	0.725148	837	1319	2928	16670	12504.3	0.0140936
89	0.212119	0.27214	0.27269	0.243051	840	1323	2918	18083	5729.02	0.0064572
90	0.18711	0.059429	0.184566	0.568896	842	1357	2961	17822	10923.6	0.0123119
91	0.212119	0.27214	0.27269	0.243051	840	1323	2918	18083	5729.02	0.0064572
92	0.298482	0.253792	0.254024	0.193701	869	1422	2995	19562	5170.26	0.0058274
93	0.163531	0.198292	0.162225	0.475953	865	1293	2881	16838	8879.31	0.0100079
94	0.413016	0.00998	0.367169	0.209835	838	1404	2985	17483	5124.66	0.005776
95	0.090074	0.127616	0.081447	0.700864	833	1319	2920	17823	12972.7	0.0146215
96	0.061905	0.105451	0.13249	0.700154	942	1372	3079	18320	13437.8	0.0151457
97	0.031164	0.14853	0.077046	0.74326	906	1342	2980	15857	12243	0.0137991
98	0.06149	0.005899	0.150834	0.781777	911	1333	2996	15953	12987.5	0.0146382
99	0.23663	0.274936	0.212571	0.275863	893	1423	3088	18457	6350.57	0.0071577
100	0.06149	0.005899	0.150834	0.781777	911	1333	2996	15953	12987.5	0.0146382

Table 5.3 Real Power Generation on six generators

trial	P_{G1}	P_{G2}	P_{G5}	P_{G8}	P_{G11}	P_{G13}
1	149.149	55.825	23.8026	27.788	11.5248	39.201
2	172.939	37.8677	16.2866	22.023	15.811	33.428
3	156.621	27.5009	31.5243	28.229	21.2267	28.086
4	116.217	43.3013	37.5775	33.439	22.666	37.645
5	121.532	69.0613	27.7639	22.931	28.615	25.87
6	91.9645	78.8705	33.1251	32.576	29.555	16.648
7	157.198	71.7194	23.5983	15.454	11.8719	21.127
8	166.959	25.0293	25.4128	31.83	23.234	20.3
9	169.107	40.2627	37.7666	12.067	22.055	27.63
10	171.08	34.1677	46.1988	21.635	19.476	13.889
11	169.326	39.0683	45.1387	10.548	17.1251	13.931
12	140.337	79.0669	22.347	30.207	19.5116	16.67
13	135.681	52.8951	28.9683	14.48	23.4204	38.528
14	103.797	64.9551	46.0759	14.134	29.192	34.71
15	154.323	29.1934	19.6938	27.9997	26.0271	34.8137
16	172.326	35.9933	17.0238	18.4848	22.9601	25.8021
17	113.133	54.3675	33.4827	26.298	17.0296	37.6832
18	145.249	34.6836	49.0581	16.8014	17.7848	37.4353
19	103.385	75.1804	37.6397	16.7578	17.343	29.2446

20	167.169	23.7455	41.6094	13.6416	13.4288	34.6852
21	145.248	51.0932	16.9869	22.5226	17.8291	39.0052
22	164.584	20.1727	46.8345	29.0732	21.4728	23.2222
23	126.564	47.8415	45.1778	17.0053	17.0823	36.6354
24	134.192	53.8743	41.0373	18.2448	22.6505	33.9287
25	173.731	24.155	29.8519	30.9566	13.5229	26.5055
26	164.771	34.1843	29.8668	20.0657	20.6074	39.1455
27	134.083	44.0005	37.6613	28.6098	18.4222	27.326
28	138.237	56.5534	43.9072	24.3975	17.2646	12.4249
29	140.529	73.8473	23.6904	25.754	16.7017	14.3749
30	122.415	62.6021	41.8682	19.4173	13.7739	31.1416
31	145.249	34.6836	49.0581	16.8014	17.7848	37.4353
32	103.385	75.1804	37.6397	16.7578	17.343	29.2446
33	167.169	23.7455	41.6094	13.6416	13.4288	34.6852
34	145.248	51.0932	16.9869	22.5226	17.8291	39.0052
35	164.584	20.1727	46.8345	29.0732	21.4728	23.2222
36	126.564	47.8415	45.1778	17.0053	17.0823	36.6354
37	134.192	53.8743	41.0373	18.2448	22.6505	33.9287
38	173.731	24.155	29.8519	30.9566	13.5229	26.5055
39	164.771	34.1843	29.8668	20.0657	20.6074	39.1455
40	134.083	44.0005	37.6613	28.6098	18.4222	27.326

41	161.432	35.1076	48.7355	17.9159	11.495	17.8495
42	159.2	57.8033	23.6615	14.0974	19.2824	23.4578
43	130.118	64.4319	33.2116	23.6042	26.5268	13.2615
44	164.584	20.1727	46.8345	29.0732	21.4728	23.2222
45	126.564	47.8415	45.1778	17.0053	17.0823	36.6354
46	134.192	53.8743	41.0373	18.2448	22.6505	33.9287
47	173.731	24.155	29.8519	30.9566	13.5229	26.5055
48	164.771	34.1843	29.8668	20.0657	20.6074	39.1455
49	134.083	44.0005	37.6613	28.6098	18.4222	27.326
50	126.564	47.8415	45.1778	17.0053	17.0823	36.6354
51	134.192	53.8743	41.0373	18.2448	22.6505	33.9287
52	173.731	24.155	29.8519	30.9566	13.5229	26.5055
53	164.771	34.1843	29.8668	20.0657	20.6074	39.1455
54	134.083	44.0005	37.6613	28.6098	18.4222	27.326
55	138.237	56.5534	43.9072	24.3975	17.2646	12.4249
56	174.655	29.7144	48.1013	10.5838	17.4374	12.7836
57	104.851	68.5653	46.1054	21.8063	19.424	21.7999
58	167.169	23.7455	41.6094	13.6416	13.4288	34.6852
59	145.248	51.0932	16.9869	22.5226	17.8291	39.0052
60	164.584	20.1727	46.8345	29.0732	21.4728	23.2222
61	134.192	53.8743	41.0373	18.2448	22.6505	33.9287

62	173.731	24.155	29.8519	30.9566	13.5229	26.5055
63	164.771	34.1843	29.8668	20.0657	20.6074	39.1455
64	194.556	26.4999	22.2337	25.0992	11.0122	27.8079
65	161.469	36.6951	37.7447	26.2064	11.6562	36.5792
66	128.161	53.7341	34.1171	34.4739	18.3781	32.985
67	114.364	60.2994	41.9203	17.2365	20.0826	39.7469
68	147.052	33.8627	42.197	12.554	12.9375	32.3601
69	127.823	50.7685	33.3551	31.4407	18.9747	38.919
70	113.611	75.771	32.3346	17.753	19.1813	31.8398
71	134.192	53.8743	41.0373	18.2448	22.6505	33.9287
72	159.144	46.9025	34.7529	18.6049	18.3034	17.6416
73	212.638	23.9243	33.4565	13.3179	10.4888	20.4412
74	198.142	41.8994	30.1973	23.0863	13.7174	12.32
75	161.432	35.1076	48.7355	17.9159	11.495	17.8495
76	159.2	57.8033	23.6615	14.0974	19.2824	23.4578
77	130.118	64.4319	33.2116	23.6042	26.5268	13.2615
78	164.584	20.1727	46.8345	29.0732	21.4728	23.2222
79	126.564	47.8415	45.1778	17.0053	17.0823	36.6354
80	134.083	44.0005	37.6613	28.6098	18.4222	27.326
81	138.237	56.5534	43.9072	24.3975	17.2646	12.4249
82	161.469	36.6951	37.7447	26.2064	11.6562	36.5792

83	128.161	53.7341	34.1171	34.4739	18.3781	32.985
84	114.364	60.2994	41.9203	17.2365	20.0826	39.7469
85	127.823	50.7685	33.3551	31.4407	18.9747	38.919
86	113.611	75.771	32.3346	17.753	19.1813	31.8398
87	161.766	49.2264	30.4824	30.8201	20.8378	17.0973
88	134.083	44.0005	37.6613	28.6098	18.4222	27.326
89	138.237	56.5534	43.9072	24.3975	17.2646	12.4249
90	140.529	73.8473	23.6904	25.754	16.7017	14.3749
91	138.237	56.5534	43.9072	24.3975	17.2646	12.4249
92	174.655	29.7144	48.1013	10.5838	17.4374	12.7836
93	104.851	68.5653	46.1054	21.8063	19.424	21.7999
94	159.2	57.8033	23.6615	14.0974	19.2824	23.4578
95	130.118	64.4319	33.2116	23.6042	26.5268	13.2615
96	164.584	20.1727	46.8345	29.0732	21.4728	23.2222
97	126.564	47.8415	45.1778	17.0053	17.0823	36.6354
98	134.192	53.8743	41.0373	18.2448	22.6505	33.9287
99	173.731	24.155	29.8519	30.9566	13.5229	26.5055
100	134.192	53.8743	41.0373	18.2448	22.6505	33.9287

Table 5.4 Reactive Power generation on six generators and corresponding Losses

Trial	Q_{G1}	Q_{G2}	Q_{G5}	Q_{G8}	Q_{G11}	Q_{G13}	Losses
1	-92.384	49.3664	43.7531	66.9544	28.3602	4.6784	11.2589
2	-56.106	53.576	50.2283	20.8552	30.0708	23.7245	12.6871
3	75.979	-32.519	-7.8093	49.8415	-1.0004	15.5474	9.46095
4	78.558	3.1779	-18.926	-2.1831	21.4289	8.0764	7.34652
5	-59.877	24.7295	89.9809	12.1326	30.1201	4.3631	9.60623
6	141.522	-37.32	-24.382	62.5027	-28.867	-0.6407	9.30607
7	-113.08	29.8401	37.7667	126.106	-4.7179	24.1606	15.4751
8	-32.394	39.1159	28.9095	10.762	58.7038	4.6607	9.42433
9	-112.03	29.2587	68.2813	65.9753	39.0207	20.1814	13.1958
10	-88.913	29.9529	18.0892	70.4843	170.403	35.3782	12.185
11	-15.171	46.1919	-24.555	64.0127	6.1596	-0.947	9.52658
12	-106.26	37.1515	41.4306	77.8343	29.2955	25.3005	12.1559
13	147.424	-35.897	-20.108	8.8092	14.6741	12.6267	11.599
14	-40.913	-8.1305	64.5542	40.9698	-11.784	38.3662	6.56414
15	42.5347	9.4221	-19.227	39.5153	1.9979	16.971	8.5592
16	0.09892	42.9788	33.8206	27.76	-23.105	13.1935	9.22101
17	134.909	-84.219	12.5305	33.5291	-28.349	18.2891	8.35057
18	-58.678	56.6316	42.2145	1.0757	39.106	15.7134	8.00089
19	118.88	-70.339	-36.762	56.3736	-0.0268	20.3952	8.8503
20	18.8876	24.2058	-19.989	41.2904	26.296	-4.4143	9.03582
21	2.2261	42.8196	-11.153	54.2809	8.9005	-0.8732	9.06628

22	-92.668	41.0198	42.9073	108.53	-27.562	9.8742	11.2788
23	-3.5257	33.2364	10.327	47.1584	5.0624	-1.3078	7.06024
24	-69.941	44.2963	48.2024	15.6851	31.2493	24.8748	8.45221
25	-75.075	40.9849	92.2405	7.8722	21.6163	23.7999	12.4003
26	-101.27	59.8266	58.5968	59.8347	-17.243	19.3324	11.4463
27	2.7988	14.9124	36.2589	12.9364	-1.6402	21.6969	6.78891
28	-11.253	-9.4175	42.1907	47.8116	12.6007	-4.6427	7.62474
29	-50.908	51.6794	38.954	64.9185	0.0191	-5.5704	8.64961
30	49.3507	-33.862	16.5099	0.0794	26.995	38.1278	7.75668
31	-58.678	56.6316	42.2145	1.0757	39.106	15.7134	8.00089
32	118.88	-70.339	-36.762	56.3736	-0.0268	20.3952	8.8503
33	18.8876	24.2058	-19.989	41.2904	26.296	-4.4143	9.03582
34	2.2261	42.8196	-11.153	54.2809	8.9005	-0.8732	9.06628
35	-92.668	41.0198	42.9073	108.53	-27.562	9.8742	11.2788
36	-3.5257	33.2364	10.327	47.1584	5.0624	-1.3078	7.06024
37	-69.941	44.2963	48.2024	15.6851	31.2493	24.8748	8.45221
38	-75.075	40.9849	92.2405	7.8722	21.6163	23.7999	12.4003
39	-101.27	59.8266	58.5968	59.8347	-17.243	19.3324	11.4463
40	2.7988	14.9124	36.2589	12.9364	-1.6402	21.6969	6.78891
41	-22.009	-11.679	30.1906	37.9054	51.4706	19.7245	9.07658
42	-62.36	40.0955	3.6485	91.8314	7.0111	8.2772	12.1801
43	51.7541	10.5869	1.7786	-2.2068	24.5268	4.9252	7.52517
44	-92.668	41.0198	42.9073	108.53	-27.562	9.8742	11.2788

45	-3.5257	33.2364	10.327	47.1584	5.0624	-1.3078	7.06024
46	-69.941	44.2963	48.2024	15.6851	31.2493	24.8748	8.45221
47	-75.075	40.9849	92.2405	7.8722	21.6163	23.7999	12.4003
48	-101.27	59.8266	58.5968	59.8347	-17.243	19.3324	11.4463
49	2.7988	14.9124	36.2589	12.9364	-1.6402	21.6969	6.78891
50	-3.5257	33.2364	10.327	47.1584	5.0624	-1.3078	7.06024
51	-69.941	44.2963	48.2024	15.6851	31.2493	24.8748	8.45221
52	-75.075	40.9849	92.2405	7.8722	21.6163	23.7999	12.4003
53	-101.27	59.8266	58.5968	59.8347	-17.243	19.3324	11.4463
54	2.7988	14.9124	36.2589	12.9364	-1.6402	21.6969	6.78891
55	-11.253	-9.4175	42.1907	47.8116	12.6007	-4.6427	7.62474
56	-59.069	43.5509	42.0975	65.7638	2.2737	3.2996	10.0145
57	138.724	-75.662	-8.4645	26.1001	-6.8023	21.1973	8.69975
58	18.8876	24.2058	-19.989	41.2904	26.296	-4.4143	9.03582
59	2.2261	42.8196	-11.153	54.2809	8.9005	-0.8732	9.06628
60	-92.668	41.0198	42.9073	108.53	-27.562	9.8742	11.2788
61	-69.941	44.2963	48.2024	15.6851	31.2493	24.8748	8.45221
62	-75.075	40.9849	92.2405	7.8722	21.6163	23.7999	12.4003
63	-101.27	59.8266	58.5968	59.8347	-17.243	19.3324	11.4463
64	-14.335	40.2412	37.7065	62.6592	-17.807	-6.3376	11.7324
65	-189.46	298.254	-21.674	8.872	35.0089	-1.6637	17.4074
66	-96.877	70.7296	5.6966	55.1939	25.6221	33.1655	8.71471
67	21.0364	-24.364	65.2394	-9.3637	15.0787	19.8876	7.35465

68	40.1409	-12.646	26.0894	-9.1242	11.516	26.2591	7.28462
69	-59.532	88.428	-2.4967	56.0188	-0.9913	17.5985	8.26415
70	3.1317	30.1556	10.0805	-5.1432	0.1061	44.5489	7.15604
71	-69.941	44.2963	48.2024	15.6851	31.2493	24.8748	8.45221
72	-96.038	38.3483	45.2282	89.5363	13.1105	18.6556	12.0442
73	-168.68	162.892	13.7266	94.3468	-10.452	22.4823	20.115
74	-115.12	36.0207	110.994	71.3305	4.1118	25.3034	18.8988
75	-22.009	-11.679	30.1906	37.9054	51.4706	19.7245	9.07658
76	-62.36	40.0955	3.6485	91.8314	7.0111	8.2772	12.1801
77	51.7541	10.5869	1.7786	-2.2068	24.5268	4.9252	7.52517
78	-92.668	41.0198	42.9073	108.53	-27.562	9.8742	11.2788
79	-3.5257	33.2364	10.327	47.1584	5.0624	-1.3078	7.06024
80	2.7988	14.9124	36.2589	12.9364	-1.6402	21.6969	6.78891
81	-11.253	-9.4175	42.1907	47.8116	12.6007	-4.6427	7.62474
82	-189.46	298.254	-21.674	8.872	35.0089	-1.6637	17.4074
83	-96.877	70.7296	5.6966	55.1939	25.6221	33.1655	8.71471
84	21.0364	-24.364	65.2394	-9.3637	15.0787	19.8876	7.35465
85	-59.532	88.428	-2.4967	56.0188	-0.9913	17.5985	8.26415
86	3.1317	30.1556	10.0805	-5.1432	0.1061	44.5489	7.15604
87	-134.65	112.887	37.8683	47.3033	28.3829	-2.0991	12.7118
88	2.7988	14.9124	36.2589	12.9364	-1.6402	21.6969	6.78891
89	-11.253	-9.4175	42.1907	47.8116	12.6007	-4.6427	7.62474
90	-50.908	51.6794	38.954	64.9185	0.0191	-5.5704	8.64961

91	-11.253	-9.4175	42.1907	47.8116	12.6007	-4.6427	7.62474
92	-59.069	43.5509	42.0975	65.7638	2.2737	3.2996	10.0145
93	138.724	-75.662	-8.4645	26.1001	-6.8023	21.1973	8.69975
94	-62.36	40.0955	3.6485	91.8314	7.0111	8.2772	12.1801
95	51.7541	10.5869	1.7786	-2.2068	24.5268	4.9252	7.52517
96	-92.668	41.0198	42.9073	108.53	-27.562	9.8742	11.2788
97	-3.5257	33.2364	10.327	47.1584	5.0624	-1.3078	7.06024
98	-69.941	44.2963	48.2024	15.6851	31.2493	24.8748	8.45221
99	-75.075	40.9849	92.2405	7.8722	21.6163	23.7999	12.4003
100	-69.941	44.2963	48.2024	15.6851	31.2493	24.8748	8.45221

Table 5.5 IEEE 30-bus 6-generator system Load Flow Results after applying Optimization

Maximum Power Mismatch = 0.273182

No. of Iterations = 6

Bus No.	Voltage	Angle	-----Load-----		---Generation---		Injected MVAR
	Mag.	Degree	MW	MVAR	MW	MVAR	
1	0.964	0.000	0.000	0.000	161.766	-134.653	0.000
2	1.000	-4.641	21.700	12.700	49.226	112.887	0.000
3	0.984	-6.217	2.400	1.200	0.000	0.000	0.000
4	0.987	-7.454	7.600	1.600	0.000	0.000	0.000
5	0.999	-11.167	94.200	19.000	30.482	37.868	0.000
6	1.003	-8.691	0.000	0.000	0.000	0.000	0.000
7	0.994	-10.246	22.800	10.900	0.000	0.000	0.000
8	1.016	-8.968	30.000	30.000	30.820	47.303	0.000

9	1.003	-10.376	0.000	0.000	0.000	0.000	0.000
10	0.978	-12.620	5.800	2.000	0.000	0.000	19.000
11	1.062	-8.044	0.000	0.000	20.838	28.383	0.000
12	0.986	-11.530	11.200	7.500	0.000	0.000	0.000
13	0.985	-10.117	0.000	0.000	17.097	-2.099	0.000
14	0.970	-12.597	6.200	1.600	0.000	0.000	0.000
15	0.964	-12.741	8.200	2.500	0.000	0.000	0.000
16	0.975	-12.309	3.500	1.800	0.000	0.000	0.000
17	0.972	-12.766	9.000	5.800	0.000	0.000	0.000
18	0.956	-13.500	3.200	0.900	0.000	0.000	0.000
19	0.955	-13.730	9.500	3.400	0.000	0.000	0.000
20	0.960	-13.518	2.200	0.700	0.000	0.000	0.000
21	0.963	-13.159	17.500	11.200	0.000	0.000	0.000
22	0.963	-13.152	0.000	0.000	0.000	0.000	0.000
23	0.951	-13.300	3.200	1.600	0.000	0.000	0.000
24	0.942	-13.651	8.700	6.700	0.000	0.000	4.300
25	0.920	-13.519	0.000	0.000	0.000	0.000	0.000
26	0.900	-14.035	3.500	2.300	0.000	0.000	0.000
27	0.916	-13.140	0.000	0.000	0.000	0.000	0.000
28	1.007	-9.186	0.000	0.000	0.000	0.000	0.000
29	0.893	-14.683	2.400	0.900	0.000	0.000	0.000
30	0.880	-15.800	10.600	1.900	0.000	0.000	0.000
Total			283.40	126.200	310.230	89.689	23.300

Table 5.6 Line Flow and Losses on IEEE 30-bus 6-generator system after applying Multi-objective OPF using GA for optimal solution (trial 87)

-----Line-----		-- Power at bus & line flow --			--Line loss--		Transformer
From	to	MW	MVAR	MVA	MW	MVAR	tap
1		161.766	-134.653	210.475			
	2	105.396	-93.051	140.594	3.992	6.862	
	3	50.648	-21.532	55.035	1.436	2.014	
2		27.526	100.187	103.900			
	1	-101.404	99.913	142.356	3.992	6.862	
	4	27.647	-2.603	27.770	0.436	-2.305	
	5	55.051	-11.527	56.244	1.472	2.006	
	6	36.212	-13.956	38.808	0.846	-1.184	
3		-2.400	-1.200	2.683			
	1	-49.213	23.545	54.555	1.436	2.014	
	4	46.824	-24.745	52.960	0.380	0.275	
4		-7.600	-1.600	7.767			
	2	-27.211	0.298	27.213	0.436	-2.305	
	3	-46.444	25.020	52.755	0.380	0.275	
	6	37.688	-48.894	61.734	0.460	0.711	
	12	28.383	22.008	35.916	0.000	3.069	0.951
5		-63.718	18.868	66.453			
	2	-53.579	13.532	55.261	1.472	2.006	
	7	-10.140	8.107	12.982	0.086	-1.810	
6		0.000	0.000	0.000			

2	-35.365	12.772	37.601	0.846	-1.184	
4	-37.228	49.605	62.021	0.460	0.711	
7	33.322	0.195	33.322	0.295	-0.788	
8	2.430	-32.904	32.994	0.126	-0.475	
9	14.105	-3.842	14.619	0.000	0.449	1.008
10	11.125	-8.850	14.216	-0.000	1.320	1.087
28	11.656	-16.791	20.440	0.040	-12.989	
7	-22.800	-10.900	25.272			
5	10.226	-9.916	14.244	0.086	-1.810	
6	-33.027	-0.983	33.041	0.295	-0.788	
8	0.820	17.303	17.323			
6	-2.304	32.429	32.511	0.126	-0.475	
28	3.107	1.437	3.423	0.014	-4.337	
9	0.000	0.000	0.000			
6	-14.105	4.291	14.744	0.000	0.449	
11	-20.838	-27.686	34.651	0.000	2.481	
10	34.943	23.395	42.052	-0.000	1.932	
10	-5.800	17.000	17.962			
6	-11.125	10.170	15.073	-0.000	1.320	
9	-34.943	-21.463	41.008	-0.000	1.932	
20	9.129	4.652	10.245	0.103	0.229	
17	5.136	5.945	7.856	0.021	0.054	
21	17.354	11.891	21.037	0.161	0.346	
22	8.650	5.805	10.418	0.082	0.170	

11	20.838	28.383	35.211		
9	20.838	30.167	36.664	0.000	2.481
12	-11.200	-7.500	13.479		
4	-28.383	-18.939	34.122	0.000	3.069
13	-17.097	0.632	17.109	0.000	0.422
14	8.070	2.330	8.399	0.089	0.186
15	18.757	6.616	19.889	0.270	0.531
16	7.455	1.861	7.684	0.057	0.121
13	17.097	-2.099	17.226		
12	17.097	-0.210	17.098	0.000	0.422
14	-6.200	-1.600	6.403		
12	-7.980	-2.144	8.263	0.089	0.186
15	1.781	0.544	1.862	0.008	0.007
15	-8.200	-2.500	8.573		
12	-18.487	-6.085	19.463	0.270	0.531
14	-1.772	-0.537	1.852	0.008	0.007
18	5.942	0.717	5.985	0.041	0.084
23	6.117	3.405	7.001	0.053	0.106
16	-3.500	-1.800	3.936		
12	-7.398	-1.740	7.600	0.057	0.121
17	3.898	-0.060	3.899	0.013	0.031
17	-9.000	-5.800	10.707		
16	-3.885	0.091	3.886	0.013	0.031
10	-5.115	-5.891	7.801	0.021	0.054

18	-3.200	-0.900	3.324		
15	-5.901	-0.633	5.935	0.041	0.084
19	2.701	-0.267	2.714	0.005	0.010
19	-9.500	-3.400	10.090		
18	-2.696	0.278	2.710	0.005	0.010
20	-6.804	-3.678	7.734	0.022	0.045
20	-2.200	-0.700	2.309		
19	6.826	3.723	7.775	0.022	0.045
10	-9.026	-4.423	10.051	0.103	0.229
21	-17.500	-11.200	20.777		
10	-17.194	-11.545	20.710	0.161	0.346
22	-0.306	0.345	0.461	0.000	0.000
22	0.000	0.000	0.000		
10	-8.568	-5.635	10.255	0.082	0.170
21	0.306	-0.345	0.461	0.000	0.000
24	8.262	5.980	10.199	0.129	0.201
23	-3.200	-1.600	3.578		
15	-6.065	-3.298	6.904	0.053	0.106
24	2.865	1.698	3.330	0.016	0.033
24	-8.700	-2.400	9.025		
22	-8.133	-5.779	9.977	0.129	0.201
23	-2.849	-1.665	3.300	0.016	0.033
25	2.282	5.044	5.537	0.065	0.114

25	0.000	0.000	0.000			
24	-2.217	-4.931	5.406	0.065	0.114	
26	3.555	2.382	4.279	0.055	0.082	
27	-1.338	2.549	2.878	0.011	0.020	
26	-3.500	-2.300	4.188			
25	-3.500	-2.300	4.188	0.055	0.082	
27	0.000	0.000	0.000			
25	1.349	-2.528	2.865	0.011	0.020	
28	-14.706	-0.946	14.736	-0.000	1.025	
29	6.223	1.733	6.460	0.109	0.207	
30	7.134	1.742	7.344	0.206	0.388	
28	0.000	0.000	0.000			
27	14.706	1.972	14.837	-0.000	1.025	1.092
8	-3.093	-5.773	6.549	0.014	-4.337	
6	-11.615	3.802	12.222	0.040	-12.989	
29	-2.400	-0.900	2.563			
27	-6.114	-1.527	6.301	0.109	0.207	
30	3.714	0.627	3.766	0.043	0.081	
30	-10.600	-1.900	10.769			
27	-6.928	-1.354	7.059	0.206	0.388	
29	-3.671	-0.546	3.711	0.043	0.081	
				11.144	1.725	

6.1 CONCLUSION

An efficient approach using Genetic Algorithm is identified to solve optimization problems. The various objectives achieved in this thesis work can be summarized as follows:

- Implementation of single-objective OPF based on Genetic Algorithm (GA). This calculates the optimum generation pattern, losses as well as other control variables in order to minimize each objective function (Fuel cost, F_1 ; NO_x Emissions, F_2 ; CO_x Emissions, F_3 ; SO_x Emissions, F_4) while the system is operating within its security limits.
- Implementation of multi-objective OPF based on Genetic Algorithm (GA) using Weightage Sum Method. An optimal solution is calculated on the basis of best fitness corresponding to various combinations of weights (w_1 , w_2 , w_3 and w_4) combined with different cases of four objective functions (F_1 , F_2 , F_3 , F_4) again while keeping the transmission system within its specified security limits.

Several populations using Genetic Algorithm have been generated to get the results. Although the computational time is higher in case of GA but its advantages like ability to adapt to changes, rapid convergence and ability to generate satisfactory solutions, over-shadows its disadvantage.

6.2 SCOPE OF FUTURE WORK

- The problem which should be addressed is the modeling of discrete variables within the OPF framework. At present, variables such as transformer tap ratios and phase shift angles are treated as continuous variables.

- The multi-objective optimal power flow solution can be further obtained by hybrid GA methods. For example: hybrid GA with Simulated Annealing etc.
- The present work of this thesis can be modified by carrying out multi-objective optimization of power system network with FACTS devices.

APPENDIX A

The data for six generator test system is given as below [32]. The Bus data, Line Data and Generator Limits are given below in Table (A1 to A3).

TABLE A1: Bus Data

Bus No.	Bus Code	Voltage Mag.	Angle Deg.	Load (MW)	Load (MVAR)	Gen (MW)	Gen (MVAR)	Gen (Q_{\min})	Gen Q_{\max}	Injected (MVAR)
1	1	1.05	0.0	0.0	0.0	50	-20	0	150	0
2	2	1.033	0.0	21.70	12.7	20	-30	0	60	0
3	0	1.0	0.0	2.4	1.2	0	0.0	0	0	0
4	0	1.0	0.0	7.6	1.6	0	0.0	0	0	0
5	2	1.0058	0.0	94.2	19.0	15	-15	0	60	0
6	0	1.0	0.0	0.0	0.0	0	0.0	0	0	0
7	0	1.0	0.0	22.0	10.9	0	0.0	0	0	0
8	2	1.023	0.0	30.0	30.0	10	-15	0	50	0
9	0	1.0	0.0	0.0	0.0	0	0.0	0	0	0
10	0	1.0	0.0	5.8	2.0	0	0.0	0	0	19
11	2	1.0913	0.0	0.0	0.0	10	-10	0	-40	0
12	0	1.0	0.0	11.2	7.5	0	0	0	0	0
13	2	1.0883	0.0	0.0	0.0	12	-15	0	45	0
14	0	1.0	0.0	6.2	1.6	0	0	0	0	0
15	0	1.0	0.0	8.2	2.5	0	0	0	0	0
16	0	1.0	0.0	3.5	1.8	0	0	0	0	0
17	0	1.0	0.0	9.0	5.8	0	0	0	0	0
18	0	1.0	0.0	3.2	0.9	0	0	0	0	0
19	0	1.0	0.0	9.5	3.4	0	0	0	0	0
20	0	1.0	0.0	2.2	0.7	0	0	0	0	0
21	0	1.0	0.0	17.5	11.2	0	0	0	0	0
22	0	1.0	0.0	0.0	0.0	0	0	0	0	0
23	0	1.0	0.0	3.2	1.6	0	0	0	0	0
24	0	1.0	0.0	8.7	6.7	0	0	0	0	0

25	0	1.0	0.0	0.0	0.0	0	0	0	0	0
26	0	1.0	0.0	3.5	2.3	0	0	0	0	0
27	0	1.0	0.0	0.0	0.0	0	0	0	0	0
28	0	1.0	0.0	0.0	0.0	0	0	0	0	0
29	0	1.0	0.0	2.4	0.9	0	0	0	0	0
30	0	1.0	0.0	10.6	1.9	0	0	0	0	0

TABLE A2: Line Data

Bus From	Bus To	R (p.u)	X (p.u)	$\frac{1}{2}B$ (p.u)	Tap at Bus
1	2	0.0192	0.0575	0.02640	1
1	3	0.0452	0.1852	0.02040	1
2	4	0.0570	0.1737	0.01840	1
3	4	0.0132	0.0379	0.00420	1
2	5	0.0472	0.1983	0.02090	1
2	6	0.0581	0.1763	0.01870	1
4	6	0.0119	0.0414	0.00450	1
5	7	0.0460	0.1160	0.01020	1
6	7	0.0267	0.0820	0.00850	1
6	8	0.0120	0.0420	0.00450	1
6	9	0.0000	0.2080	0.00000	0.978
6	10	0.0000	0.5560	0.00000	0.969
9	11	0.0000	0.2080	0.00000	1
9	10	0.0000	0.1100	0.00000	1
4	12	0.0000	0.2560	0.00000	0.932
12	13	0.0000	0.1400	0.00000	1
12	14	0.1231	0.2599	0.00000	1
12	15	0.0662	0.1304	0.00000	1

12	16	0.0945	0.1987	0.00000	1
14	15	0.2210	0.1997	0.00000	1
16	17	0.0824	0.1923	0.00000	1
15	18	0.1073	0.2185	0.00000	1
18	19	0.0639	0.2192	0.00000	1
19	20	0.0340	0.0680	0.00000	1
10	20	0.0936	0.2090	0.00000	1
10	17	0.0324	0.0845	0.00000	1
10	21	0.0348	0.0749	0.00000	1
10	22	0.0727	0.1499	0.00000	1
21	22	0.0116	0.0236	0.00000	1
15	23	0.1000	0.2020	0.00000	1
22	24	0.1150	0.1790	0.00000	1
23	24	0.1320	0.2700	0.00000	1
24	25	0.1885	0.3292	0.00000	1
25	26	0.2544	0.3800	0.00000	1
25	27	0.1093	0.2087	0.00000	1
28	27	0.0000	0.3960	0.00000	0.1968
27	29	0.2198	0.4153	0.00000	1
27	30	0.3202	0.6027	0.00000	1
29	30	0.2399	0.4533	0.00000	1
8	28	0.0636	0.2000	0.02140	1
6	28	0.0169	0.0599	0.06500	1

TABLE A3: Generator Limits

MW(minimum)	MW(maximum)	MVAR(minimum)	MVAR(maximum)
50	200	-30	150
20	80	-30	60
15	50	-15	60
10	35	-15	50
10	30	-10	40
12	40	-15	45

TABLE A4: Cost Coefficients

Bus No.	a	b	c
1	0.00375	2	0
2	0.01750	1.75	0
5	0.06250	1.00	0
8	0.00834	3.25	0
11	0.02500	3	0
13	0.02500	3	0

TABLE A5: NO_x Emission Coefficients

Bus No.	a	b	c
1	0.006323	-0.38128	80.9019
2	0.006483	-0.79027	28.8249
5	0.003174	-1.36061	32401775
8	0.006732	-2.39928	610.2535
11	0.003174	-1.36061	324.1775
13	0.006181	-0.39077	50.1775

TABLE A6: SO_x Emission Coefficients

Bus No.	a	b	c
1	0.001206	5.09928	51.3778
2	0.002320	3.84654	182.2605
5	0.001248	4.45647	508.5207
8	0.000813	4.97641	165.3433
11	0.001248	4.45647	508.5207
13	0.003578	4.14938	121.2133

TABLE A7: SO_x Emission Coefficients

Bus No.	a	b	c
1	0.265110	-61.01945	5080.148
2	0.140053	-29.95221	3824.770
5	0.105929	-9.552794	1342.851
8	0.106409	-12.73642	1819.625
11	0.105929	-9.552794	1342.857
13	0.403144	-121.9812	11381.070

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