EP based Optimal Power Flow Solutions

Thesis submitted in partial fulfillment of the requirements for the award of degree of

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Certificate

I hereby certify that the work which is being presented in the thesis entitled, **"EP based Optimal Power Flow solutions"**, in partial fulfillment 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, Sr. Lecturer, EIED.

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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This is to certify that the above statement made by the candidate is correct and true to the best of my knowledge.

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Abstract

The objective of the work presented in this report is to make an EP based algorithm for solving the optimal power flow (OPF) problem without and with compensating device. The objective in the OPF problem formulation is the minimization of total cost of real power generation. The proposed method solves the OPF problem subject to the power balance equality constraints, limits on the control variables namely active power generations, controllable voltage magnitudes, limits on the dependent variables namely reactive power generations and load bus voltage magnitudes and limits on MVA line flows as the inequality constraints. The individual cost of each generating unit is assumed to be function, only of active power generation and are represented by quadratic curves of second order. Earlier, a wide variety of optimization techniques have been applied to solving the OPF problems such as nonlinear programming (NLP), quadratic programming (QP), linear programming, Newton-based techniques, and interior point methods. But, because of certain drawbacks, such as insecure convergence properties, algorithmic complexity, and convergence characteristics. These, local optimization techniques are not suitable for such a problem. Moreover, there is no local criterion to decide whether a local solution is also the global solution. Therefore, conventional optimization methods that make use of derivatives and gradients, in general, are not able to locate or identify the global optimum. Hence, it becomes essential to develop optimization techniques that are efficient to overcome these drawbacks and handle such difficulties. Thus, heuristic algorithm i.e. evolutionary programming, has been proposed for solving the OPF problem. The OPF solution is obtained using EP for the IEEE-30 bus system.

The compensating device is also included in the power system network to study its role or its impact on the power system network. The compensating device included in this study is the series capacitor. The role of series capacitor used here in the problem is to improve the power transfer capability of the line while keeping a marginal variation in cost.

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CHAPTER 1
Introduction

1.1 Overview

Throughout the entire world, the electric power industry has undergone a considerable change in the past decade and will continue to do so for the next several decades. In the past the electric power industry has been either a government-controlled or a government-regulated industry which existed as a monopoly in its service region. All people, businesses, and industries were required to purchase their power from the local monopolistic power company. This was not only a legal requirement, but a physical engineering requirement as well. It just didn't appear feasible to duplicate the resources required to connect everyone to the power grid. Over the past decade, however, countries have begun to split up these monopolies in favour of the free market. Numerous papers and articles have been written on this topic with a good overview of the topic found in a series of articles written for IEEE Spectrum in July and August of 1996 [15, 42]. In the United States, the change from the regulated monopoly to the free market system has become known as restructuring. For the remainder of this thesis, it will be referred to as restructuring. One of the cornerstones of any restructuring plan is the ability to operate the transmission system in a manner which is fair to all participants in the industry. In the United States, the Federal Energy Regulatory Commission (FERC) oversees issues involving the transmission system. FERC presently believes that the only manner in which everyone will be on an equal playing field is to create open access to all. It was also seen that participants in wholesale power markets will have non-discriminatory open access to the transmission systems of public utilities."

In order to achieve the ideal of open access, many outstanding engineering problems will need to be investigated and tools created for their solution. It is very important that these problems be addressed early in the restructuring process. If these engineering problems become overshadowed by short term economic concerns, then the result could be decreased electricity reliability. In the past year, the western United States has seen the consequences of pushing the transmission system too hard on two separate occasions.

In a presently unpublished report from a joint PSERC/EPRI workshop, certain problem had been noticed in power system [44].

Control Problems

- Computation of real-time available transfer capability (ATC)
- Real-time control of power flows
- Tools to relieve congestion in fair, justifiable and economic manner
- Tools for congestion management (including congestion pricing)
- Tools for determining the ISO action before the contingency occurs

Economic Problems

- Real-time pricing and price risk management services
- Tools for operating the power system in the most economical manner
- Transaction evaluation tools that enable players to evaluate their own costs
- Methodologies for determining the value (cost) of ancillary services in improving efficiency and flexibility

User-Interface and Simulation Problems

- Market simulation models
- Better tools for communication and display of information will permit the better operation of the min ISO scenario

The work presented in this thesis utilizes an optimal power flow program, OPF, as the tool for solving some of these problems. The OPF is a natural choice for addressing these concerns because it is basically an optimal control problem. The OPF utilizes all control variables to help minimize the costs of the power system operation. It also yields valuable economic information and insight into the power system. Therefore, it seems, the OPF very adeptly addresses both the control and economic problems.

The power system can be improved by using compensating devices. In case of active power OPF, the main conventional control variables are MW generations based on minimum generation cost. If some predefined transmission line power flows are controlled at specified values, it may cost higher with the generation schedule. Thus, the use of Optimal Power Flow is increasingly being recognized by power utilities due to increased presence of independent power producers combined with deregulation of the power industry. Hence there is an urgent need for optimal and sophisticated power flow control i.e., solution to OPF incorporating FACTS devices.

The reactive power compensation of AC transmission systems using fixed series capacitors is applied here to solve some of the above problems associated with AC networks.

1.2. Literature Review

The optimal power flow problem has been discussed since its introduction by Carpentier in 1962 [18]. Scientists have studied about optimal power flow and described the challenges to optimal power flow. Because the OPF is a very large, non-linear mathematical programming problem, it has taken decades to develop efficient algorithms for its solution. Many different mathematical techniques have been employed for its solution. The majority of the techniques discussed in the literature use one of the following five methods.

- Lambda iteration method - Also called the equal incremental cost criterion (EICC) method. This method has its roots in the common method of economic dispatch used since the 1930s. [5]
- Gradient method - by Dommel and Tinney [16]
- Newton's method -by Sun et al. [10]
- Linear programming method -by Alsac et al. [38]
- Interior point method -by Wu, Debs, and Marsten [49]

. The drawback in applying linear programming is that the input-output function is to be expressed as a set of linear functions, which may lead to loss of accuracy. Also, they are not guaranteed to the global optimum of the general non-convex OPF problem. The gradient based methods shows certain problems in handling inequality constraints. Constrained optimization problems present the differences of potentially non-convex or even disjoint feasible regions. Classical linear programming and non-linear programming methods are often either unsuitable or impractical when applied to these constrained problems. In Newton OPF, the inequality constraints are added as quadratic penalty terms to the problem objective multiplied by appropriate penalty multiplier. This Newton method suffers from the difficulty in handling inequality constraints. Moreover, the NLP and QP methods depend on convexity to obtain the global optimum solution. Emerging artificial intelligence (AI) based methods have overcome some of the shortcomings of the mathematical programming techniques.

EP and GA are the techniques which have given solution to various problems in power system The EP technique is a stochastic optimization method in the area of evolutionary computation, which uses the mechanics of evolution to produce optimal solutions to a given problem. It works by evolving a population of candidate solutions toward the global minimum through the use of a mutation operator and selection scheme. A number of evolutionary inspired optimization techniques were developed i.e. Bremermann in 1962 [14], Jason Yuryevich in 1999[19], Weerakorn Ongsakul in 2004[48], Latha Kumari in 2004[27], R Gnanadass in 2004[39], Dr. Y R Sood in 2005[12], Zulmar S. Machado Jr in Aug,2005[50], M Basu in Sep,2005[31], M.A.Abido in July,2006[29].

Compensation devices are implemented to produce an acceptable voltage profile, minimise the loss of the investments and enhance the power transmission capability. Shunt capacitor can be used for various purposes in power system. The most cost effective-method of improving voltage profile on feeders is accomplished by placing shunt capacitor banks on the primary distribution transmission lines. This is achieved by positioning shunt capacitor banks as close as possible to the loads that require additional reactive power. Most power system loads and distribution feeders with transformers and overhead lines are inductive in nature and, hence operate on a lagging power factor. When operating at a lagging power factor, a power system needs to draw reactive power. This results in reduced capacity of the system, increased system losses and reduced system voltage. By installing a shunt capacitor bank on the primary transmission lines, the capacity of system is increased and the system losses are reduced. Various researchers [32, 47] have given various applications of shunt capacitor in power system.

SERIES compensation is a means of improving the performance of transmission as well as distribution circuits. Today, many series capacitors are being installed on radial distribution circuits, especially those with industrial customers. The application of series compensation makes the line or circuit appear electrically shorter because it reduces the total effective reactance. Some of the positive effects provided by series compensation are improved circuit voltage profile, reduced voltage fluctuations, higher circuit capacity, and a reduced demand for reactive power from the power system. J.W. Butler and C. Concordia had done an Analysis of series capacitor application in 1937[22]. D. M. Sauter had given a study on voltage fluctuations on power systems [11]. M. V. D. Lat and G. Bonadie had given a scheme for overvoltage protection of series capacitor banks on high voltage distribution systems [33]. J. S. Hedin and L. H. Paulsson in 1993 gives the application and evaluation for compact series compensation for distribution networks [21]. In 1991, General Electric Corporation gives application and design considerations for distribution series capacitor [37].

Flexible AC Transmission System (FACTS) is a technology-based concept that can provide a full dynamic control over active and reactive power flow on transmission systems based on the key control variables such as transmission line impedance, phase angle and voltage. It also provides the needed corrections of transmission functionality in order to fully utilize existing transmission system and therefore, minimizing the gap between the stability and thermal levels. The concept of FACTS and FACTS controllers was first defined by Hingorani, 1988 [35]. They are high power electronics devices used to control the power flow and enhance stability, have become, not only common words in the power industry, but they have started replacing many mechanical control devices. They are certainly playing an important and a major role in the operation and control of modem power systems.

1.3 Scope of Work

From the above literature review, it has been seen that the OPF can be applied based on various classical and artificial intelligence techniques. Also, certain FACTS devices are also being incorporated for improving the system. However, it is observed that there is a scope to improve the OPF by applying various constraints and then by , we can also improve the system other needs like power transfer capability, reduction in losses, etc by applying FACTS devices.

The aim of the proposed work is to apply evolutionary programming technique to optimal power flow to improve the optimal power flow solution. Also, series capacitor is being used to improve the power transfer capability of the system with a marginal increase in cost.

1.4 Organization of Thesis

Chapter 1 shows the overview of the problem. Here, a literature review is done on OPF including the effect of compensating devices.

Chapter 2 tells about optimal power flow. Also, the goals of OPF and the objective of OPF is effectively described in this chapter.

Chapter 3 describes about Evolutionary programming, its description and an algorithm with a flowchart to show its effectiveness in optimal power flow.

Chapter 4 shows the incorporation of series capacitor to the power system. Here, an overview of series capacitor is described with its advantages and application. Also, an algorithm with results is given to prove its effectiveness.

Chapter 5 shows the conclusion of this thesis work and discusses the future scope of the work.

Chapter 2

Optimal Power Flow

2.1 Introduction

. In deregulated environment of power sector, it is of increasing importance, for determination of electricity prices and also for congestion management. The OPF optimizes a power system operating objective function, while satisfying a set of system constraints. Generally, the OPF problem is a large-scale, highly constrained, nonlinear problem. Optimal Power Flow (OPF) is one among the most important algorithms available to utility for generating least cost generation patterns in a power system satisfying transmission and operational constraints. OPF problem is a large dimension no-linear, non-convex and highly constrained optimization problem.

A wide variety of optimization techniques have been applied to solving the OPF problems such as nonlinear programming (NLP), quadratic programming (QP), linear programming, Newton-based techniques, and interior point methods. Generally, NLP based procedures have many drawbacks, such as insecure convergence properties and algorithmic complexity. QP-based techniques have some disadvantages associated with the piecewise quadratic cost approximation. Newton-based techniques have a drawback of the convergence characteristics that are sensitive to the initial conditions, and they may even fail to converge due to the inappropriate initial conditions. Although LP methods are fast and reliable, they have some disadvantages associated with the piecewise linear cost approximation. Interior point methods have been reported as computationally efficient; however, if the step size is not chosen properly, the sub linear problem may have a solution that is infeasible in the original nonlinear domain. Unfortunately, the problem of the OPF is a highly nonlinear and a multimodal optimization problem (i.e., there exist more than one local optimum). Hence, local optimization techniques, which are well elaborated, are not suitable for such a problem. Moreover, there is no local criterion to decide whether a local solution is also the global solution. Therefore, conventional optimization methods that make use of derivatives and gradients, in general, are not able to locate or identify the global optimum. On the other hand, many mathematical assumptions, such as convex, analytic, and differential objective functions, have to be given to simplify the problem; however, the OPF problem is an optimization problem with, in general, nonconvex, nonsmooth, and nondifferentiable objective functions. Hence, it becomes essential to develop optimization techniques that are effcient to overcome these drawbacks and handle such difficulties. Recently, heuristic algorithms, such as genetic algorithms (GA) and evolutionary programming, have been proposed for solving the OPF problem [46].

2.2 Goals of the OPF

Before beginning the creation of an OPF, it is useful to consider the goals that the OPF will need to accomplish. 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 system may depend on the situation, but in general they can be attributed to the cost of generating power (megawatts) at each generator. From the viewpoint of an OPF, the maintenance of system security needs keeping each device in the power system within its desired operation range at steady-state. This will include maximum and minimum outputs for generators, maximum MVA flows on transmission lines and transformers, as well as keeping system bus voltages within specified ranges. It should be noted that the OPF only addresses steady-state operation of the power system.

To achieve these goals, the OPF will perform all the control functions of the power system. These functions may include generator control and transmission system control. For generators, the OPF will control generator MW outputs as well as generator voltage. For the transmission system, the OPF may control the tap ratio or phase shift angle for variable transformers, switched shunt control, and all other flexible ac transmission system (FACTS) devices. A secondary goal of an OPF is the determination of system marginal cost data. This marginal cost data can aid in the pricing of MW transactions as well as the pricing ancillary services such as voltage support through MVAR support.

2.3 Optimal Power Flow Problem

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 objective function of entire power system can then be written as the sum of the quadratic cost model at each generator [2, 6, 9, and 17].

$$F(x) = \sum_{i=1}^{ng} (a_i + b_i Pg_i + c_i Pg_i^2)$$

where,

ng is number of generators including the slack bus, Pgi is the generated active power at bus i.

ai ,bi ,ci are the unit costs curve for ith generator

The cost is optimized with the following constraints.

Equality constraints

The equality constraints are as follows:

- The power flow equation of the network

$$g(V,\phi) = 0$$

$$\text{where } g(V,\phi) = \begin{cases} \left.\begin{array}{l} P_i(V,\phi) - P_i^{net} \\ Q_i(V,\phi) - Q_i^{net} \end{array}\right\} \leftarrow \text{For each PQ bus i} \\ \left.P_m(V,\phi) - P_m^{net}\right\} \leftarrow \text{For each PV bus m, not including the Ref.bus} \end{cases}$$

where

P_i and Q_i are respectively calculated real and reactive power for PQ bus i.

P_i^{net} and Q_i^{net} are respectively specified real and reactive power for PQ buses i.

P_m and P_m^{i} are respectively calculated and specified real power for PV bus m.

V and ϕ are voltage magnitude and phase angles at different buses.

Inequality constraints:

The types of inequality constraints are bus voltage limits at generations, maximum line loading limits and limits on tap settings. The various inequality constraints are as follows [17, 43]:

- The inequality constraint on real power generation at bus i

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

where Pg_i^{min} and Pg_i^{max} are resp. minimum and maximum values of real power generation allowed at generator bus i.

- The inequality constraint on reactive power generation Qg_i at each PV bus.

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

Where Q_{gi}^{min} and Q_g^{max} are respectively minimum and maximum value of reactive power at PV bus i.

- The inequality constraint on voltage magnitude V of each PQ bus.

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

where V_i^{min} and V_i^{max} are respectively minimum and maximum voltage at bus i.

- The inequality constraint on phase angle ϕ_i of voltage at all buses i.

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

Where ϕ_i^{min} and ϕ_i^{max} are respectively minimum and maximum phase angle at bus i.

- MVA flow limit on transmission line

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

Where,

MVA_{ij}^{max} is the maximum rating of transmission line connecting bus i and j.

Chapter 3

EP BASED OPF

3.1 Introduction

Evolutionary Programming is search algorithms based on the mechanics of natural selection and natural genetics. Evolutionary Programming, originally conceived by Lawrence J. Fogel in 1960, is a stochastic optimization strategy similar to Genetic Algorithms, but instead places emphasis on the behavioral linkage between parents and their offsprings, rather than seeking to emulate specific Genetic operators as observed in nature. Evolutionary programming is similar to EVOLUTION STRATEGIEs, although the two approaches developed independently. Like both ES and GAs, EP is a useful method of optimization when other techniques such as gradient descent or direct, analytical discovery are not possible. Combinatory and real-valued FUNCTION OPTIMIZATION in which the optimization surface or FITNESS landscape is “rugged", possessing many locally optimal solutions, are well suited for evolutionary programming. Before discussing Evolutionary based OPF, it is advisable to discuss Evolutionary programming [3, 7, 30]

3.2 Overview of Evolutionary Programming

L. J. Fogel presents evolutionary Programming (EP). He initially studied this method to develop the artificial intelligence and succeeded in evolving a mathematical automaton that predicts a binary time series. Later, in the middle of 80’s, his son David Fogel further developed it to solve more general tasks including prediction problems, optimization, and machine learning. Since this approach modeled organic evolution at the level of evolving species, the original EP does not rely on any kind of recombination. Evolutionary programming (EP) is a stochastic optimization strategy, which places emphasis on the behavioral linkage between parents and their offspring. It is a powerful and general optimization method, which does not depend on the first and second derivatives of the objective function and the constraints of the problem. Evolutionary programming is a probabilistic search technique, which generates the initial parent vectors distributed uniformly in intervals within the limits and obtains global optimum solution over number of iterations. The main stages of this technique are initialization, creation of off – spring vectors by mutation and competition and selection of best vectors to evaluate best fitness solution [34]. As the history of the field suggests there are many different variants of Evolutionary Algorithms. The common underlying idea behind all these techniques is the same: given a population of individuals the environmental pressure causes natural selection (survival of the fittest) and this causes a rise in the fitness of the population. Given a quality function to be maximized we can randomly create a set of candidate solutions, i.e., elements of the function’s domain, and apply the quality function as an abstract fitness measure – the higher the better. Based on this fitness, some of the better candidates are chosen to seed the next generation by applying recombination and/or mutation to them. Recombination is an operator applied to two or more selected candidates (the so-called parents) and results one or more new candidates (the children). Mutation is applied to one candidate and results in one new candidate. Executing recombination and mutation leads to a set of new candidates (the offspring) that compete based on their fitness (and possibly age) – with the old ones for a place in the next generation. This process can be iterated until a candidate with sufficient quality (a solution) is found or a previously set computational limit is reached. In this process there are two fundamental forces that form the basis of evolutionary systems.

- Variation operator (mutation) create the necessary diversity and thereby facilitates novelty, while
- Selection acts as a force pushing quality.

The combined application of variation and selection generally leads to improving fitness values in consecutive populations. It is easy (although somewhat misleading) to see such a process as if the evolution is optimizing, or at least “approximating”, by approaching optimal values closer and closer over its course[36]. Alternatively, evolution it is often seen as a process of adaptation. From this perspective, the fitness is not seen as an objective function to be optimized, but as an expression of environmental requirements. Matching these requirements more closely implies an increased viability, reflected in a higher number of offspring. The evolutionary process makes the population adapts to the population adapt to the environment better and better. Let us note that many components of such an evolutionary process are stochastic. During selection fitter individuals have a higher chance to be selected than less fit ones, but typically even the weak individuals have a chance to become a parent or to survive. For mutation, the pieces that will be mutated with in a candidate solution and the new pieces replacing them are chosen randomly. The evaluation (fitness) function represents a heuristic estimation of solution quality and the variation and the selection operators drive the search process.

The most important advantage of EP is that it uses only the objective function information and hence independent of the nature of the search space such as smoothness, convexity or uni-modality, etc [4, 46]. The optimization algorithm based on EP revolves around three processes namely natural selection, mutation and competition. Depending on the characteristics of the optimization problem each process could be modified and configured to achieve the optimum result. Evolutionary Algorithms (EA) posses a number of features that can help to position them within in the family of generate-and-test methods:

- EAs are population based, i.e., they process a whole collection of candidate solutions simultaneously,
- EAs are stochastic

The conferences attract a diverse group of academic, commercial and military researchers engaged in both developing the theory of the EP technique and in applying EP to a wide range of optimization problems, both in engineering and biology. In 1992, the First Annual Conference on evolutionary programming was held in La Jolla, CA. The 1966 book, "Artificial Intelligence Through Simulated Evolution" by Fogel, Owens and Walsh is the landmark publication for EP applications, although many other papers appear earlier in the literature. In the book, finite state automata were evolved to predict symbol strings generated from Markov processes and non-stationary time series. Such evolutionary prediction was motivated by a recognition that prediction is a keystone to intelligent behavior (defined in terms of adaptive behavior, in that the intelligent organism must anticipate events in order to adapt behavior in light of a goal).

3.3 EP vs. Classical methods

The characteristics which make EP differ from other classical methods are as follows:

- EP requires only the evaluation of the fitness function, which is formed from objective function so that every solution could be given a quality value.
- EP operates on the encoded string of the problem parameters rather than the actual parameters of the problem.
- EP has an advantage over quadratic programming, non-linear programming in the sense that these methods suffer from the difficulty in handling inequality constraints.
- EP uses a population of points rather than a single point in their search.
- EP also results in less loss of accuracy
- Classical methods are not guaranteed to converge to the global optimum of the general non-convex optimum problem where as EP has this advantage of converging into a global optimum.

3.4 Aim of using EP

An optimal power flow solution gives the optimal active and reactive power dispatch. It is a non-linear programming problem with large number of variables and equality and inequality types of limit constraints pertaining to base case operating state.

The optimal power flow solution has one primary limitation—which it does not cater for system security constraints pertaining to outage case states. Security assessment calculations are carried out in system planning and operation considering a series of contingencies involving “credible” outages of transmission circuits and generating plant. Given a base case operating condition the security assessment resolves the load-flow problem for each outage case in turn to detect potential overloads and unacceptable voltage levels. Any insecurity detected by the security assessment must be corrected in the base-case operating condition. However the security assessment gives no automatic indication of the corrections required in the base case. Assuming that the insecurities can be removed without changing the system composition the problem is then to re-schedule the controllable system quantities in such a way that the operating condition becomes secure and optimal according to an economic objective. Several optimization techniques, such as linear programming, non-linear programming, quadratic programming and interior point method are used for solving the security constrained optimal power flow problem. Dommel and Tinney presented a penalty function based NLP technique to solve optimal power flow problem. Alsac and Stott extended the penalty function method to security constrained optimal power flow problem in which all the contingency case constraints are augmented to the optimal power flow problem. In this method the functional inequality constraints are handled as soft constraints using penalty function technique. The drawback of this approach is the difficulty involved in choosing proper penalty weights for different systems and different operating conditions which if not properly selected may lead to excessive oscillatory convergence[26,45]. This combined with prohibitively large computing time makes this method not suitable for on-line implementation.

Evolutionary programming is a probabilistic search technique, which generates the initial parent vectors distributed uniformly in intervals within the limits and obtains global optimum solution over number of iterations. Evolutionary Programming is search algorithms based on the mechanics of natural selection. The most important advantage of EP is that it uses only the objective function information and hence independent of the nature of the search space such as smoothness, etc. EP based algorithms are increasingly applied for solving power system optimization problems in recent years. The OPF problems with various constraints have been solved effectively by using EP.

3.5 Components of Evolutionary Programming

Application or definition of Evolutionary Programming require certain steps, components, procedures or operators that must be specified in order to define a particular EA. The most important components are:

- Representation (definition of individuals)
- Evaluation function (or fitness function)
- Population
- Parent selection mechanism
- Variation operators like mutation

- Survivor selection mechanism (replacement)

Each of these components must be specified in order to define a particular EA. Furthermore, to obtain a running algorithm the initialization procedure and a termination condition must be also defined [25, 26].This is shown in the block diagram given below.

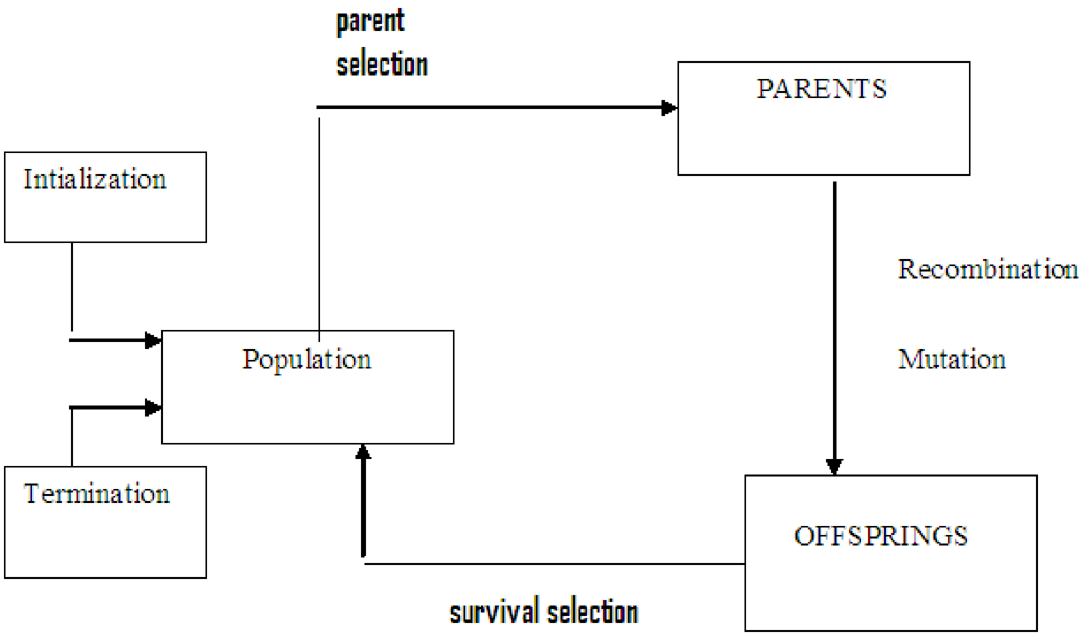


Fig: The general scheme of Evolutionary Programming

3.5.1 Representation (Definition of Individuals)

The first design step is commonly called representation, as it amounts to specifying a mapping from the phenotypes onto a set of genotypes that are said to represent these phenotypes which means to link the" real world" to the "EA world", that is to set up a bridge between the original problem context and the problem solving space where evolution will take place. Objects forming possible solutions within the original problem context are referred to as phenotypes, their encoding, the individuals within the EA, are called genotypes. For instance, given an optimization problem on integers, the given set of integers would form the set of phenotypes. Then one could decide to represent them by their binary code, hence 18 would be seen as a phenotype and 10010 as a genotype representing it. It is necessary to understand that the phenotype space can be very different from the genotype space, and that the whole evolutionary search takes place in the genotype space. A solution – a good phenotype – is obtained by decoding the best genotype after termination. To this end, it should hold that the (optimal) solution to the problem at hand – a phenotype – is represented in the given genotype space.

The common EA terminology uses many synonyms for naming the elements of these two spaces. From the side of the original problem context, candidate solution, phenotype, and individual are used to denote points of the space of possible solutions. This space itself is commonly called the phenotype space. On the side of the EA, genotype, chromosome, and again individual can be used for points in the space where the evolutionary search will actually take place. This space is also called the genotype space. Also for the elements of individuals there are many synonymous terms. A placeholder is commonly called a variable, a locus (plural: loci), a position, or – in biology oriented terminology – a gene. An object on such a place can be called a value or an allele. It should be noted that the word "representation" is used in two slightly deferent ways. Sometimes it stands for the mapping from the phenotype to the genotype space. In this sense it is synonymous with encoding, e.g., one could mention binary representation or binary encoding of candidate solutions. The inverse or reverse mapping from genotypes to phenotypes is usually called decoding and it is required that the representation be invertible: to each genotype there has to be at most one corresponding phenotype. The word representation can also be used in a slightly deferent sense, where the emphasis is not on the mapping itself, but on the "data structure" of the genotype space.

3.5.2 Evaluation Function (Fitness Function)

Evaluation function represents the task to solve in the evolutionary context. Technically, it is a function or procedure that assigns a quality measure to genotypes. More accurately, it defines what improvement means. The role of the evaluation function is to represent the requirements to adapt to. It forms the basis for selection, and thereby it facilitates improvements [3].

Typically, this function is composed from a quality measure in the phenotype space and the inverse representation.

3.5.3 Population

Population means how many individuals have in it i.e. setting the population size. . As opposed to variation operator, that act on one or two parent individuals, the selection operators (the parent selection and survival selection) work at population level. In general, the take the whole population into account and choices are always made relative to what we have. For instance, the best individual of the given population is chosen to be replaced by a new one. In almost all EPs applications, the population size is constant, not changing during the evolutionary search. The objective of population is to hold (the representation of) possible solutions. A population is a multiset of genotypes. The population forms the unit of evolution. Individuals are static objects not changing or adapting. It is the population that does.

The diversity of a population is a measure of the number of different solutions present. No single measure for diversity exists; typically people might refer to the number of different fitness values present, the number of phenotypes present, or the number of different genotypes.

3.5.4 Parent Selection Mechanism

Chromosomes are selected from the population to be parents. The problem is how to select these chromosomes. According to Darwin's evolution theory the best ones should survive and create new offspring. The objective of parent selection or mating selection is to compare among the individuals based on their quality, and to allow the better individuals to become parents of the next generation. An individual is a parent if it has been selected to undergo variation in order to create offspring. Together with the survivor selection mechanism, parent selection is responsible for pushing quality improvements. Thus, high quality individuals get a higher chance to become parents than those with low quality. However, low quality individuals are often given a small, but positive chance; otherwise the whole search would become too greedy and get stuck in a local optimum.

There are many methods how to select the best chromosomes, for example roulette wheel selection, Boltzman selection, tournament selection, rank selection, steady state selection and some others which are explain below:

3.5.4.1 Roulette Wheel Selection

Parents are selected according to their fitness. The better the chromosomes are, the more chances to be selected they have. Imagine a roulette wheel where are placed all chromosomes in the population, every one has its place big accordingly to its fitness function. Then a marble is thrown there and selects the chromosome. Chromosome with bigger fitness will be selected more times.

3.5.4.2 Rank Selection

In the roulette wheel selection, the problem is when the fitnesses differs very much. For example, if the best chromosome fitness is 90% of all the roulette wheel then the other chromosomes will have very few chances to be selected. But, Rank selection first ranks the population and then every chromosome receives fitness from this ranking. The worst will have fitness 1, second worst will have 2 etc. and the best will have fitness N (number of chromosomes in population). After this all the chromosomes have a chance to be selected. But this method can lead to slower convergence, because the best chromosomes do not differ so much from other ones.

3.5.4.3 Steady-State Selection

This is not a particular method of selecting parents. The main idea of this selection is that big part of chromosomes should survive to the next generation. EP then works in a following way. In every generations a few (good with high fitness) chromosomes are selected for creating a new offspring. Then some (bad with low fitness) chromosomes are removed and then, the new offspring is placed in their place. The rest of population survives to the new generation.

3.5.4.4 Elitism

Elistism is quite different. When creating a new population by crossover and mutation, we have a big chance that we will loose the best chromosome. Elitism is the name of a method which first copies the best chromosome (or a few best chromosomes) to the new population.

3.5.5 Mutation

The variation operator is commonly called mutation. It is applied to one genotype and delivers a (slightly) modified mutant, the child or offspring of it. A mutation operator is always stochastic: its output- the child- depends on the outcome of a series of random choices. A problem specific heuristic operator acting on one individual could be termed as mutation. However, in general mutation is to cause a random, unbiased change. It is worth noting that variation operators form the Evolutionary implementation of the elementary steps within the search space. Generating a child amounts to stepping to a new point in this space. From this point: mutation has a theoretical role too: it can guarantee that the space is connected. This is important since theorems starting that an EA will discover the global optimum of a given problem often rely on the property that each genotype representing a possible solution can be reached by the variation operator. The simplest way to satisfy this condition is to allow the mutation operation to jump everywhere [13].

Each parent vector Pg_i generates an offspring vector by adding a Gaussian random variable with mean zero and pre-selected standard deviation to each individual of Pg_i. The K parents create K off springs thus resulting in 2K individuals in the competing pool.

3.5.6 Survivor Selection Mechanism

The role of survivor selection is to distinguish among individuals based on their quality. In that it is similar to parent selection, but it is used in different stage of evolutionary cycle. The survival selection mechanism is called after having created the offspring of the selected parents. A choice has to be made on which individuals will be allowed in the next generation. This decision is usually based on their fitness values, favoring those with higher quality. Survivor selection is also often called replacement selection or replacement strategy. In many cases, the two terms can be used interchangeably. The choice between the two is often arbitrary. The preference for using replacement can be motivated by the skewed proportion of the number of individuals in the population and the number of newly created children. In particular, if the number of children is quite small with respect to the population size e.g., 2 children and a population of 100. In this case, the survivor selection step is as simple as to choose the two old individuals that are to be deleted to make place for the new ones. In other words, it is more efficient to declare that everybody survives unless deleted and to choose whom to replace. If the proportion is not skewed like this, e.g., 500 children made from a population of 100, and then this is not an option, so using the term survivor selection is appropriate. Each individual in the competing pool is evaluated for its fitness. All individuals compete with each other for selection. The best K individuals with maximum fitness values are retained to be parents of the next generation. The process of creating off spring and selecting those with maximum fitness are repeated until there is no appreciable improvement in the maximum fitness value or it is repeated up to a pre specified number of iterations.

3.5.7 Initialization

Initialization is the first step which is applied while using Evolutionary Programming. Here, problem specific heuristics can be used in this step aiming at an initial population with higher fitness. Thus, population is selected based on certain measures. Whether this is worth the extra computational effort or not is very much depending on the application at hard. Here, an initial population of parent individuals (Pg_i , i = 1, 2, 3 ……k) is generated randomly within a feasible range in each dimension.

3.5.8 Termination condition

Termination means the end of the technique or application which we are using in the system. As for a suitable termination condition we can distinguish two cases. If the problem has a known optimal fitness level, probably coming from a known optimum of the given objective function, then reaching this level should be used as a stopping condition. However, EPs are stochastic and therefore, there are no guarantees to reach an optimum, hence the condition might never get satisfied and the algorithm may never stop. This requires that this condition is extended with one that certainly stops the algorithm. Commonly used options for this purpose are the following:

- The maximum allowed CPU time elapses;
- The total number of fitness evaluations reaches a given limit;
- For a given period of time (i.e. for a number of generations or fitness evaluations),the fitness improvement remains under a threshold value;
- The population diversity drops under a given threshold.

The actual termination criterion in such cases is a disjunction: optimum value hit or condition satisfied. If the problem does not have a known optimum, then we need no disjunction, simply a condition from the above list or a similar one that is guaranteed to stop the algorithm.

3.6 Algorithm & Flowchart of EP based OPF

3.6.1 Algorithm

Step-by-step algorithm for Evolutionary Programming based optimal power flow (EP-OPF) has been described below.

Step1. First of all, we input the database for the generator data, bus data, capacitor/reactor data, transformer data and transmission line data[23].

Step2. Here, suitably population size (pop_size), maximum number of generations or populations (gen_max) has been assumed.

Step3. Set valid number of population counter.pop_vn=0.

Step4. A random number is used to initialize randomly each of the control variables of an individual within its feasible range.

Step5. Run power flow using the Newton-Raphson method for each set of generating patterns Pg_i corresponding to a particular generation and hence determine, slack bus generation, bus voltage magnitudes and phase angle at all the buses.Then, calculate power flow in each transmission line of the system.

Step6. Check the following constraints,

- Check the voltage phase violation

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

- Check the bus voltage phase angle

  $Ø_i^{min} \leq Ø_i \leq Ø_i^{max}$

If any of the above limits is violated, go to step 4.

Step7.If all the constraints are satisfied, increment pop_vn by 1. If pop_vn less than or equal to pop_size, go to step 4, otherwise go to next step.

Step8. In this step, we find out the cost and fitness corresponding to each valid generation pattern of an individual candidate in the population. In this computation, the fitness of each individual is defined as follows.

$Ft_i = A/cost_i$ for $i = 1$ to pop_size

where,

A is very large constant.

$cost_i$ = cost corresponding to i^{th} individual

ft_i = fitness value of function for i^{th} individual

Step9. Find and store maximum fitness ft_{max} and minimum cost among all valid individual parents and corresponding generation pattern.

Step10. A new population is produced from the existing population through the mutation operator. A new individual Pg_i^{new} is produced from each old (parent) individual Pg_i^{old}. The j^{th} OPF variable px_{ji}^{new} in the new individual Pg_i^{new} is calculated as:

$$Pg_{ji}^{new} = Pg_i^{old} + N\ (0,\sigma_{ji}^2)$$

where Pg_{ji}^{new} is the value of variable j in the parents Pg_i^{old}.

$N\ (0, \sigma_{ji}^2)$ is a Gaussian random number with a mean of zero and a standard deviation of σ_{ji}. The expression designed for σ_{ji} is given below.

$$\sigma_{ji} = (Pg_{ji}^{max} - Pg_{ji}^{min})\ ((ft_{max} - ft_i)/ft_{max} + ap)$$

where

ft_i is the fitness of individual i

ft_{max} is the maximum fitness

Pg_{ji}^{max} and Pg_{ji}^{min} denote the upper and lower limits of variable j

'ap' is a positive number constant slightly less than unity.

Step11. Check the Px_j(value of OPF variable j), it should be between Pg_j^{max} and Pg_j^{min}, otherwise this individual in the population is rejected.

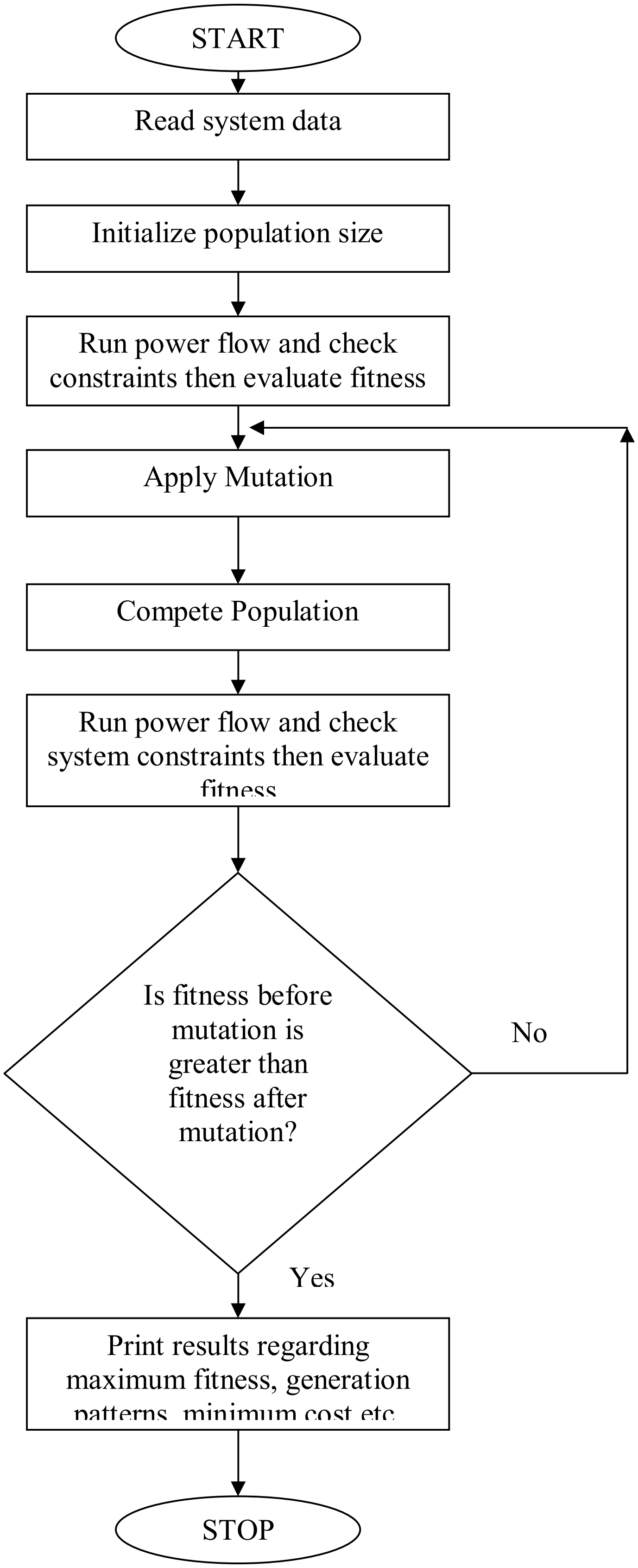
Step12. Run power flow using Newton-Raphson method for each set of new OPF variables satisfying constraint of step 12 and hence determine, slack bus generation, bus voltage magnitudes and phase angles at all the buses. Also calculate power flow in each transmission line of the system.

Step13. Again, check the system constraints as mentioned in step 6. If all the constraints are satisfied, the individual of the new population becomes valid otherwise it becomes invalid.

Step14. Find the maximum fitness among all valid individuals. If it is more than ft_{max}, store this fitness in ft_{max} and also store corresponding OPF variables.

Step15. Find the optimum solution among all population groups.

3.6.2 Flowchart



3.7 Results and Discussion

The Evolutionary Programming based optimization method is applied to the IEEE 30 bus system. Its bus data, line data and cost coefficients are given in Appendix A.

After running load flow, the generation values of different generators are:

Table 3.7.1: Optimal generation before applying EP

Generator	MW
1	229.571
2	20.00
3	15.00
4	10.00
5	10.00
6	12.00

- Total loss is 13.221MW and 18.265 Mvar.
- Total cost for dispatch is 833.27 $/hr.

Table 3.7.2: Optimal generation after applying EP

Generator	MW
1	177.6885
2	38.4613
3	25.7691
4	17.6922
5	16.1538
6	16.9006

- Total cost for this dispatch is 806.9779 $/hr.

Evolutionary Programming based optimal power flow method is successfully implemented on IEEE 30 bus test system. Here, initially, we generate a random number and by using that random number, the load flow analysis is done. From this we get different values of generations for each generator. Then on applying mutation process, optimal power generation and optimal cost is obtained while maintaining some constraints within limits.

CHAPTER 4
EP based OPF with Series Capacitor

4.1 Introduction

For the improvement of power system, various compensation devices had been used. Series and shunt compensation had been used for improving various measures like power transfer capability, reduction in losses etc. Implementation of FACTS is also one of the techniques to improve the power system. The concept of flexible AC transmission systems (FACTS) was first proposed by Hingorani [34]. Flexible alternating-current transmission systems (FACTS) are defined by the IEEE as “ac transmission systems incorporating power electronics-based and other static controllers to enhance controllability and increase power transfer capability” [1]. Similarly, a FACTS controller is defined as “a power electronics-based system or other static equipment that can provide control of one or more ac transmission parameters”. In recent years, many different FACTS controllers have been proposed, and performing a wide variety of functions. FACTS devices have the ability to allow power systems to operate in a more flexible, secure, economic, and sophisticated way. Generation patterns that lead to heavy line flows result in higher losses, and weakened security and stability. Such patterns are economically undesirable. Further, transmission constraints make certain combinations of generation and demand unviable due to the potential of outages. In such situations, FACTS devices may be used to improve system performance by controlling the power flows in the grid. Studies on FACTS so far have mainly focused on device developments and their impacts on the power system aspects such as control, transient and small signal stability enhancement, and damping of oscillations. Here we look at solving the OPF problem in a power system incorporating FACTS devices. As we have seen in the earlier chapters, different solution approaches are possible to solve the OPF problem. The main conventional control variables are the generation MWs when the DC power flow model is used. With the increased presence of independent gencos in the deregulated scenario, the operation of power systems would require more sophisticated means of power control. FACTS devices can meet that need.

4.2 Overview on Series Capacitor

Series compensation is a means of improving the performance of transmission as well as distribution circuits. Today, many of the series capacitors are being installed on radial distribution circuits, especially those with industrial customers. The application of series compensation makes the line or circuit appear electrically shorter because it reduces the total effective reactance. Some of the positive effects provided by series compensation are improved circuit voltage profile, reduced voltage fluctuations, higher circuit capacity, and a reduced demand for reactive power from the power system [40].

Adding a series capacitor to a radial circuit results in reducing the reactance of that circuit. For the normal case of lagging power factor loads, adding the series capacitor reduces the voltage drop associated with the load current for all loads on the circuit downstream from the series capacitor. Also, the series capacitor acts as a voltage regulator that provides a boost in voltage at the capacitor location that is proportional to the circuit current magnitude and the sine of the power factor angle. Moreover, this boost in voltage is both instantaneous and continuous, which makes the concept a natural choice where rapidly changing loads are present. So, a typical use for series capacitors on distribution circuits is to reduce voltage variations on those circuits caused by large varying inductive loads. This is fundamentally different than the response of a switched shunt capacitor, which cannot be smoothly responsive to rapid load changes.

4.3Advantages of using Series Capacitor

The use of distribution series capacitors is, very often, associated with very long radial power distribution circuits supplying remote customers [22, 41]. The application of series capacitors will provide the following advantages:

- Increased power transmission capability by a decreased total circuit reactance and improved voltage profile along the circuit
- Decreased circuit losses
- Improved voltage regulation and reactive power balance
- Support during start of large asynchronous and synchronous motors
- Reduction of required reactive power input at the sending end of a radial circuit.
- Improved division of current between parallel circuits

- Self-regulating, continuous and instantaneous response
- Reduced voltage fluctuations due to load variations
- No over voltages are created due to load rejection

A moderate increase in short circuit currents for faults downstream from the series capacitor without an increased fault level at the substation.

4.4 Applications

The most common application for series capacitors in power distribution circuits is to reduce voltage drops due to load current and improve the voltage profile along the circuit thereby increasing the loadability of the circuit. The benefit is the greatest on circuits with rapidly varying loads. Since the voltage across the series capacitor and the radial circuit reactance is proportional to the circuit current, the series capacitor provides continuous and virtually instantaneous voltage regulation in case of relatively rapid variations of the load. Thus, the series capacitor gives a continuous and instantaneous voltage control determined by the actual load current. This action provides very effective voltage regulation if the major portion of the voltage drop is associated with the circuit reactance.

Additional positive effects of a series capacitor in a radial power distribution circuit are: the reduction in reactive power requirements of the circuit, the reduction of circuit losses because of the increased voltage, the improvement of load division between parallel circuits and the voltage support (reactive power support) during starting of asynchronous and synchronous motors.

In all of these applications, the capability of the series capacitor to compensate for the circuit inductance is being utilized.

A. Increase of the Steady-State Voltage—Improvement of the Voltage Profile

The ability of the series capacitor to reduce drops in the steady-state voltage and improve the voltage profile of a power distribution circuit for inductive loads.

B. Reduction of Voltage Fluctuations

In cases of voltage fluctuations due to large variations of the load, a series capacitor will improve the voltage quality at the loads downstream from the series capacitor.

C. Reduction of Required Feeder Reactive Power Input

The series capacitor improves the power factor. This means that the required reactive power input to the sending end of the line can be decreased.

D. Reduction of the Circuit Losses

The losses in a radial power distribution circuit are proportional to the square of the circuit current. A series capacitor installed in the circuit with an inductive load will increase the voltage at the receiving end. This implies a reduction of the circuit current resulting in decreased circuit losses as circuit losses are proportional to current.

4.5 Problem formulation of OPF with Series Capacitor

The objective of an Optimal Power Flow (OPF) algorithm is to find the steady-state operation point of a generation transmission system, which minimizes a pre-specified cost function and meets a set of operational and/or security constraints. For optimal active and reactive power dispatch the objective function that is total generation cost and other objectives may include minimization of transmission losses and voltage level optimization. In case of active power OPF, the main conventional control variables are MW generations based on minimum generation cost. If some predefined transmission line power flows are controlled at specified values, it may cost higher with the generation schedule. OPF algorithms are among the tools present in many Energy Management Systems (EMS) and their usefulness is increasingly being recognized by power utilities due to increased presence of independent power producers combined with deregulation of the power industry. Hence there is an urgent need for optimal and sophisticated power flow control i.e., solution to OPF incorporating FACTS devices.

The reactive power compensation of AC transmission systems using fixed series capacitors is applied here to solve some of the above problems associated with AC networks.

Here, series capacitor is used to improve the reactive power capability of the line without causing a major increase in the cost.

4.6 Algorithm

Step-by-step algorithm for Evolutionary Programming based optimal power flow (EP-OPF) with series capacitor has been described below:-

Step1. The optimum results of EP-OPF has been taken and seen that whether considerable reactive power compensation could be done or not.

Step2. If yes, then the line is noticed and a equivalent capacitance value is entered on the line by replacing this entered value by the line data's reactance value.

Step3. Run power flow using the Newton-Raphson method for each set of generating patterns Pg_i corresponding to a particular generation and hence determine, slack bus generation, bus voltage magnitudes and phase angle at all the buses. Also calculate power flow in each transmission line of the system.

Step4. Corresponding to the above results, the cost is calculated.

Step5. Value of fixed capacitance is derived by carrying out the following equation:

$$c = 1/ (2*3.14*50*Xc)$$

4.7 Results and Discussion

Here, by using the series capacitor, the compensation is done on line no 13-12. The value of fixed capacitor used is 0.1562 p.u.

Results before the series capacitor has been applied:-

Table 4.7.1: Power flow solution before applying series capacitor

Bus No.	Voltage Mag.	Angle Degree	---Load---- MW	Mvar	---Generation-- MW	Mvar	Injected Mvar
1	1.05	0	0	0	177.628	-11.346	0
2	1.033	-3.706	21.7	12.7	38.461	7.286	0
3	1.032	-5.66	2.4	1.2	0	0	0
4	1.027	-6.797	7.6	1.6	0	0	0
5	1.006	-9.85	94.2	19	25.769	21.392	0
6	1.022	-7.91	0	0	0	0	0
7	1.008	-9.237	22.8	10.9	0	0	0
8	1.023	-8.276	30	30	17.692	35.47	0
9	1.043	-9.639	0	0	0	0	0
10	1.038	-11.467	5.8	2	0	0	19
11	1.081	-7.948	0	0	16.154	25.547	0
12	1.046	-10.565	11.2	7.5	0	0	0
13	1.088	-9.374	0	0	16.901	33.35	0
14	1.031	-11.408	6.2	1.6	0	0	0
15	1.027	-11.624	8.2	2.5	0	0	0

16	1.035	-11.227	3.5	1.8	0	0	0
17	1.032	-11.607	9	5.8	0	0	0
18	1.018	-12.277	3.2	0.9	0	0	0
19	1.016	-12.469	9.5	3.4	0	0	0
20	1.021	-12.278	2.2	0.7	0	0	0
21	1.025	-11.908	17.5	11.2	0	0	0
22	1.025	-11.891	0	0	0	0	0
23	1.017	-12.027	3.2	1.6	0	0	0
24	1.012	-12.213	8.7	6.7	0	0	0
25	1.019	-12.18	0	0	0	0	0
26	1.002	-12.598	3.5	2.3	0	0	0
27	1.033	-11.888	0	0	0	0	0
28	1.017	-8.408	0	0	0	0	0
29	1.013	-13.095	2.4	0.9	0	0	0
30	1.002	-13.96	10.6	1.9	0	0	0
Total			283.4	126.2	292.605	111.699	19

Table 4.7.2: Line flows and losses before applying series capacitor

--Line--		Power at bus and line flow			---Line loss--		Transformer tap
From	to	MW	Mvar	MVA	MW	Mvar	
1		177.628	-11.346	177.99			
	2	120.198	-8.059	120.468	2.521	1.821	
	3	57.46	-3.28	57.554	1.354	1.126	
2		16.761	-5.4141	17.613			
	1	-117.68	9.88	118.091	2.521	1.821	
	4	31.003	-7.884	31.989	0.532	-2.284	
	5	61.477	0.528	61.479	1.675	2.15	
	6	41.959	-7.911	42.698	0.978	-0.983	
3		-2.4	-1.200 5	2.683			
	1	-56.106	4.406	56.279	1.354	1.126	
	4	53.706	-5.606	53.998	0.361	0.145	
4		-7.6	-1.6	7.766			
	2	-30.471	5.6	30.981	0.532	-2.284	
	3	-53.346	5.751	53.655	0.361	0.145	
	6	48.991	-1.433	49.012	0.271	-0.003	
	12	27.225	-11.518	29.561	0	2.175	1.013

5		-68.431	2.392	68.472			
	2	-59.802	1.622	59.824	1.675	2.15	
	7	-8.629	0.781	8.664	0.035	-1.979	
6		0	0	0			
	2	-40.981	6.928	41.563	0.978	-0.983	
	4	-48.721	1.43	48.742	0.271	-0.003	
	7	31.739	7.232	32.552	0.274	-0.909	
	8	14.255	-6.325	15.595	0.027	-0.846	
	9	15.235	-17.379	23.112	0	1.096	1.016
	10	12.295	4.939	13.25	0	0.866	0.963
	28	16.179	3.176	16.487	0.045	-1.193	
7		-22.8	-10.9	25.271			
	5	8.664	-2.759	9.093	0.035	-1.979	
	6	-31.464	-8.141	32.5	0.274	-0.909	
8		-12.308	5.47	13.468			
	6	-14.227	5.48	15.246	0.027	-0.846	
	28	1.919	0.041	1.92	0.005	-4.438	
9		0	0	0			
	6	-15.235	18.476	23.947	0	1.096	
	11	-16.006	-18.955	24.809	0	1.177	
	10	31.389	5.492	31.866	0	1.027	
10		-5.8	17	17.962			
	6	-12.295	-4.073	12.952	0	0.866	
	9	-31.389	-4.465	31.705	0	1.027	
	20	9.094	4.294	10.056	0.088	0.196	
	17	5.262	5.632	7.707	0.018	0.047	
	21	15.86	10.618	19.086	0.118	0.253	
	22	7.669	4.995	9.153	0.057	0.117	
11		16.154	25.547	30.225			
	9	16.006	20.132	25.719	0	1.177	
12		-11.2	-7.5	13.479			
	4	-27.225	13.692	30.474	0	2.175	

	13	-16.901	-31.722	35.943	0	1.654	
	14	7.307	2.292	7.658	0.066	0.137	
	15	18.301	6.092	19.288	0.225	0.444	
	16	7.318	2.146	7.626	0.05	0.106	
13		16.901	33.35	37.388			
	12	16.901	33.377	37.412	0	1.654	
14		-6.2	-1.6	6.403			
	12	-7.241	-2.155	7.555	0.066	0.137	
	15	1.041	0.555	1.179	0.003	0.007	
15		-8.2	-2.5	8.572			
	12	-18.076	-5.648	18.938	0.225	0.444	
	14	-1.038	-0.548	1.174	0.003	0.007	
	18	5.955	1.025	6.042	0.037	0.076	
	23	4.959	2.671	5.632	0.03	0.061	
16		-3.5	-1.8	3.935			
	12	-7.267	-2.041	7.548	0.05	0.106	
	17	3.767	0.241	3.775	0.011	0.026	
17		-9	-5.8	10.707			
	16	-3.756	-0.215	3.762	0.011	0.026	
	10	-5.244	-5.585	7.661	0.018	0.047	
18		-3.2	-0.9	3.324			
	15	-5.918	-0.95	5.993	0.037	0.076	
	19	2.718	0.05	2.718	0.005	0.009	
19		-9.5	-3.4	10.090			
	18	-2.713	-0.04	2.713	0.005	0.009	
	20	-6.787	-3.36	7.573	0.019	0.038	
20		-2.2	-0.7	2.308			
	19	6.806	3.397	7.607	0.019	0.038	
	10	-9.006	-4.097	9.894	0.088	0.196	
21		-17.5	-11.2	20.777			

	10	-15.742	-10.364	18.847	0.118	0.253	
	22	-1.758	-0.836	1.947	0	0.001	
22		0	0	0			
	10	-7.613	-4.878	9.042	0.057	0.117	
	21	1.759	0.836	1.947	0	0.001	
	24	5.854	4.042	7.114	0.055	0.086	
23		-3.2	-1.6	3.577			
	15	-4.929	-2.61	5.577	0.03	0.061	
	24	1.729	1.01	2.002	0.005	0.01	
24		-8.7	-6.7	10.980			
	22	-5.799	-3.956	7.02	0.055	0.086	
	23	-1.724	-0.999	1.993	0.005	0.01	
	25	-1.177	-1.745	2.105	0.008	0.014	
25		0	0	0			
	24	1.186	1.759	2.121	0.008	0.014	
	26	3.544	2.366	4.262	0.044	0.066	
	27	-4.73	-4.126	6.276	0.041	0.079	
26		-3.5	-2.3	4.188			
	25	-3.5	-2.3	4.188	0.044	0.066	
27		0	0	0			
	25	4.771	4.205	6.36	0.041	0.079	
	28	-18.048	-7.526	19.554	0	1.322	
	29	6.188	1.664	6.407	0.085	0.16	
	30	7.089	1.657	7.28	0.159	0.299	
28		0	0	0			
	27	18.048	8.848	20.1	0	1.322	0.958
	8	-1.914	-4.478	4.87	0.005	-4.438	
	6	-16.134	-4.37	16.715	0.045	-1.193	
29		-2.4	-0.9	2.563			
	27	-6.103	-1.504	6.286	0.085	0.16	
	30	3.703	0.604	3.752	0.033	0.062	

30		-10.6	-1.9	10.768			
	27	-6.93	-1.358	7.062	0.159	0.299	
	29	-3.67	-0.542	3.71	0.033	0.062	
Total loss					9.235	4.218	

Results after the series capacitor has been applied:-

Table 4.7.3: Power flow solution after applying series capacitor

Bus	Voltage	Angle	---Load----		---Generation---		Injected
No.	Mag.	Degree	MW	Mvar	MW	Mvar	Mvar
1	1.05	0	0	0	177.659	-11.407	0
2	1.033	-3.705	21.7	12.7	38.461	7.319	0
3	1.032	-5.664	2.4	1.2	0	0	0
4	1.027	-6.801	7.6	1.6	0	0	0
5	1.006	-9.848	94.2	19	25.769	21.494	0
6	1.022	-7.902	0	0	0	0	0
7	1.008	-9.232	22.8	10.9	0	0	0
8	1.023	-8.272	30	30	17.692	36.023	0
9	1.04	-9.614	0	0	0	0	0
10	1.037	-11.437	5.8	2	0	0	19
11	1.081	-7.901	0	0	16.154	21.781	0
12	1.048	-10.602	11.2	7.5	0	0	0
13	1.088	-9.584	0	0	16.901	36.242	0
14	1.034	-11.436	6.2	1.6	0	0	0
15	1.028	-11.641	8.2	2.5	0	0	0
16	1.036	-11.232	3.5	1.8	0	0	0
17	1.031	-11.587	9	5.8	0	0	0
18	1.019	-12.276	3.2	0.9	0	0	0
19	1.017	-12.459	9.5	3.4	0	0	0
20	1.021	-12.262	2.2	0.7	0	0	0
21	1.024	-11.881	17.5	11.2	0	0	0
22	1.024	-11.865	0	0	0	0	0
23	1.018	-12.033	3.2	1.6	0	0	0
24	1.011	-12.203	8.7	6.7	0	0	0
25	1.019	-12.172	0	0	0	0	0
26	1.002	-12.59	3.5	2.3	0	0	0
27	1.033	-11.881	0	0	0	0	0
28	1.017	-8.401	0	0	0	0	0

29	1.013	-13.088	2.4	0.9	0	0	0
30	1.002	-13.954	10.6	1.9	0	0	0
Total			283.4	126.2	292.636	111.452	19

Table 4.7.4: Line flows and losses after applying series capacitor

--Line--		Power at bus and line flow			---Line loss--		Transformer tap
from	To	MW	Mvar	MVA	MW	Mvar	
1		177.659	-11.407	178.025			
	2	120.175	-8.053	120.445	2.52	1.818	
	3	57.487	-3.353	57.584	1.355	1.131	
2		16.761	-5.381	17.603			
	1 -	-117.66	9.871	118.069	2.52	1.818	
	4	31.031	-7.98	32.041	0.534	-2.28	
	5	61.467	0.53	61.469	1.675	2.148	
	6	41.92	-7.797	42.639	0.975	-0.99	
3		-2.4	-1.2	2.683			
	1	-56.131	4.484	56.31	1.355	1.131	
	4	53.731	-5.684	54.031	0.361	0.146	
4		-7.6	-1.6	7.767			
	2	-30.497	5.7	31.025	0.534	-2.28	
	3	-53.37	5.83	53.688	0.361	0.146	
	6	48.725	-0.54	48.728	0.268	-0.014	
	12	27.542	-12.59	30.283	0	2.282	1.013
5		-68.431	2.494	68.476			
	2	-59.792	1.618	59.814	1.675	2.148	
	7	-8.639	0.878	8.683	0.036	-1.978	
6		0	0	0			
	2	-40.945	6.807	41.507	0.975	-0.99	
	4	-48.458	0.526	48.461	0.268	-0.014	
	7	31.749	7.135	32.54	0.274	-0.909	
	8	14.256	-6.764	15.779	0.028	-0.843	
	9	15.026	-15.93	21.899	0	0.985	1.016

	10	12.201	5.119	13.231	0	0.864	0.963
	28	16.171	3.106	16.467	0.045	-1.193	
7		-22.8	-10.9	25.272			
	5	8.675	-2.856	9.132	0.036	-1.978	
	6	-31.475	-8.044	32.486	0.274	-0.909	
8		-12.308	6.023	13.703			
	6	-14.228	5.92	15.41	0.028	-0.843	
	28	1.92	0.112	1.923	0.006	-4.436	
9		0	0	0			
	6	-15.026	16.915	22.625	0	0.985	
	11	-16.154	-20.48	26.084	0	1.309	
	10	31.18	3.565	31.383	0	1.002	
10		-5.8	17	17.962			
	6	-12.201	-4.255	12.922	0	0.864	
	9	-31.18	-2.563	31.285	0	1.002	
	20	9	3.821	9.778	0.083	0.186	
	17	5.146	4.79	7.03	0.015	0.039	
	21	15.804	10.372	18.903	0.116	0.249	
	22	7.632	4.835	9.034	0.055	0.114	
11		16.154	21.781	27.117			
	9	16.154	21.789	27.124	0	1.309	
12		-11.2	-7.5	13.479			
	4	-27.542	14.872	31.301	0	2.282	
	13	-16.901	-34.635	38.538	0	1.621	
	14	7.333	2.425	7.723	0.067	0.139	
	15	18.473	6.843	19.7	0.234	0.46	
	16	7.437	2.995	8.017	0.055	0.116	
13		16.901	36.242	39.988			
	12	16.901	36.256	40.001	0	1.621	
14		-6.2	-1.6	6.403			
	12	-7.266	-2.286	7.617	0.067	0.139	

	15	1.066	0.686	1.268	0.003	0.008	
15		-8.2	-2.5	8.573			
	12	-18.239	-6.383	19.324	0.234	0.46	
	14	-1.063	-0.679	1.261	0.003	0.008	
	18	6.045	1.49	6.226	0.039	0.08	
	23	5.057	3.072	5.917	0.033	0.067	
16		-3.5	-1.8	3.936			
	12	-7.382	-2.878	7.923	0.055	0.116	
	17	3.882	1.078	4.029	0.012	0.029	
17		-9	-5.8	10.707			
	16	-3.869	-1.049	4.009	0.012	0.029	
	10	-5.131	-4.751	6.992	0.015	0.039	
18		-3.2	-0.9	3.324			
	15	-6.006	-1.41	6.169	0.039	0.08	
	19	2.806	0.51	2.852	0.005	0.01	
19		-9.5	-3.4	10.09			
	18	-2.801	-0.5	2.845	0.005	0.01	
	20	-6.699	-2.9	7.3	0.018	0.035	
20		-2.2	-0.7	2.309			
	19	6.717	2.936	7.33	0.018	0.035	
	10	-8.917	-3.636	9.63	0.083	0.186	
21		-17.5	-11.2	20.777			
	10	-15.688	-10.123	18.671	0.116	0.249	
	22	-1.812	-1.077	2.108	0	0.001	
22		0	0	0			
	10	-7.576	-4.721	8.927	0.055	0.114	
	21	1.813	1.078	2.109	0	0.001	
	24	5.764	3.643	6.819	0.051	0.079	
23		-3.2	-1.6	3.578			
	15	-5.024	-3.005	5.854	0.033	0.067	

	24	1.824	1.405	2.302	0.007	0.014	
24		-8.7	-6.7	10.981			
	22	-5.713	-3.564	6.733	0.051	0.079	
	23	-1.817	-1.391	2.288	0.007	0.014	
	25	-1.17	-1.745	2.101	0.008	0.014	
25		0	0	0			
	24	1.178	1.759	2.117	0.008	0.014	
	26	3.544	2.366	4.262	0.044	0.066	
	27	-4.723	-4.126	6.271	0.041	0.079	
26		-3.5	-2.3	4.188			
	25	-3.5	-2.3	4.188	0.044	0.066	
27		0	0	0			
	25	4.764	4.205	6.354	0.041	0.079	
	28	-18.041	-7.526	19.547	0	1.322	
	29	6.188	1.664	6.407	0.085	0.16	
	30	7.089	1.657	7.28	0.159	0.299	
28		0	0	0			
	27	18.041	8.848	20.093	0	1.322	0.958
	8	-1.914	-4.548	4.934	0.006	-4.436	
	6	-16.126	-4.3	16.69	0.045	-1.193	
29		-2.4	-0.9	2.563			
	27	-6.103	-1.504	6.286	0.085	0.16	
	30	3.703	0.604	3.752	0.033	0.062	
30		-10.6	-1.9	10.769			
	27	-6.93	-1.358	7.062	0.159	0.299	
	29	-3.67	-0.542	3.71	0.033	0.062	
					Total	Total	
					9.239	4.29	

Thus, from the above results, we can see that the voltage at bus no.13 remains same from 1.088 to 1.088 and the voltage at bus no. 12 is changed from 1.046 to 1.048.Also, the line flows at line no 13-12 is changed from 33.377 to 36.256.

Similarly, below are the results on other lines where the series capacitor is implemented. The following table is showing the variation in the voltage magnitudes at the lines where is series capacitor is being incorporated.

Table 4.7.5: Voltage magnitudes on different line without and with application of series capacitor

Line no.		Voltage mag.(before)	Voltage mag.(after)
13-12	13	1.088	1.088
	12	1.046	1.048
12-4	12	1.046	1.044
	4	1.027	1.027
11-9	11	1.081	1.081
	9	1.043	1.041
28-27	28	1.017	1.017
	27	1.033	1.033
8-6	8	1.023	1.023
	6	1.022	1.023
6-2	6	1.022	1.022
	2	1.033	1.033
4-3	4	1.027	1.027
	3	1.032	1.033
4-2	4	1.027	1.0271
	2	1.033	1.033

Table 4.7.6: Line flows and losses without and with application of series capacitor

Line flows and losses(before)							Line flows and losses(after)						
--Line--		Power at bus and line flow			---Line loss--		--Line--		Power at bus and line flow			---Line loss--	
from	to	MW	Mvar	MVA	MW	Mvar	from	to	MW	Mvar	MVA	MW	Mvar
13		16.901	33.35	37.388		1.654	**13**		16.901	36.242	39.988		
	12	16.901	**33.377**	37.412	0			**12**	16.901	**36.256**	40.001	0	1.621
12		-11.2	-7.5	13.479		2.175	**12**		-11.2	-7.5	13.479		
	4	-27.225	**13.692**	30.474	0	1.654		**4**	-28.113	**14.258**	31.522	0	2.15
	13	-16.901	-31.722	35.943	0	0.137		13	-16.901	-32.65	36.765	0	1.735
	14	7.307	2.292	7.658	0.066	0.444		14	7.378	2.318	7.733	0.068	0.14
	15	18.301	6.092	19.288	0.225	0.106		15	18.705	6.22	19.711	0.236	0.465
	16	7.318	2.146	7.626	0.05			16	7.732	2.355	8.082	0.057	0.119
11		16.154	25.547	28.534		1.177	**11**		16.154	23.522	28.534		
	9	16.006	**20.132**	25.719	0			**9**	16.154	**23.525**	28.537	0	1.309
28		0	0	0		1.322	**28**		0	0	0		
	27	18.048	**8.848**	20.1	0	-4.438		**27**	18.41	**9.015**	20.499	0	1.302
	8	-1.914	-4.478	4.87	0.005	-1.193		8	-1.991	-4.708	5.112	0.006	-4.433
	6	-16.134	-4.37	16.715	0.045			6	-16.419	-4.307	16.974	0.046	-1.187
8		-12.308	5.47	15.238			**8**		-12.308	8.984	15.238		
	6	-14.227	**5.48**	15.246	0.027	-0.846		**6**	-14.98	**9.312**	17.639	0.037	-0.874
	28	1.919	0.041	1.92	0.005	-4.438		28	2.673	-0.308	2.69	0.007	-4.435

6		0	0	0			**6**		0	0	0		
	2	-40.981	**6.928**	41.563	0.978	-0.983		**2**	-43.551	**8.425**	44.359	1.116	-0.945
	4	-48.721	1.43	48.742	0.271	-0.003		4	-46.846	0.305	46.847	0.25	-0.073
	7	31.739	7.232	32.552	0.274	-0.909		7	32.429	6.656	33.105	0.284	-0.878
	8	14.255	-6.325	15.595	0.027	-0.846		8	14.28	-8.004	16.37	0.03	-0.836
	9	15.235	-17.379	23.112	0	1.096		9	15.171	-15.727	21.852	0	0.981
	10	12.295	4.939	13.25	0	0.866		10	12.285	5.32	13.388	0	0.885
	28	16.179	3.176	16.487	0.045	-1.193		28	16.231	3.026	16.51	0.045	-1.191
4		-7.6	-1.6	7.767			**4**		-7.6	-1.6	7.767		
	2	-30.471	5.6	30.981	0.532	-2.284		2	-29.178	4.807	29.572	0.485	-2.426
	3	-53.346	**5.751**	53.655	0.361	0.145		**3**	-56.076	**6.662**	56.47	0.4	-0.349
	6	48.991	-1.433	49.012	0.271	-0.003		6	50.212	-1.706	50.241	0.285	0.046
	12	27.225	-11.518	29.561	0	2.175		12	27.442	-11.363	29.702	0	2.197
4		-7.6	-1.6	7.767			**4**		-7.6	-1.6	7.767		
	2	-30.471	**5.6**	30.981	0.532	-2.284		**2**	-32.436	**6.737**	33.128	0.61	-2.259
	3	-53.346	5.751	53.655	0.361	0.145		3	-52.613	5.125	52.862	0.351	0.117
	6	48.991	-1.433	49.012	0.271	-0.003		6	50.015	-2.037	50.057	0.283	0.04
	12	27.225	-11.518	29.561	0	2.175		12	27.434	-11.425	29.718	0	2.201

Thus, from the above results, we can see that the table 4.7.5 is showing the variation in voltage at different buses after the implementation of series capacitor. Also, the increase in power transfer is noticed at different lines after the application of series capacitor in the table 4.7.6.

Thus, the series capacitor has been successfully applied in the power system. The role of series capacitor is to improve the power transfer capability of the line with a marginal increase in cost, which has been successfully implemented in the power system. Here, a fixed value of capacitance is applied on different line numbers and the reactive power capability of line has been improved with a marginal increase in cost.

Chapter 5

Conclusion and Future Work

5.1 Conclusion

The Evolutionary Programming based Optimal Power Flow problem has been explored and tested without and with compensating device. The results show that a simple evolutionary based algorithm can give a best result using only simple evolutionary operations such as mutation. Thus, in large-scale system, where the number of constraints is very large, it is necessary to use the methodology like EP which results to give optimum solution and capable of handling such type of problems. The Evolutionary Programming based technique without and with compensating device is applied and validated on the IEEE30 bus system

The compensating device included in this study is the series capacitor. The role of series capacitor used here in the problem is to improve the power transfer capability of the line while keeping a marginal variation in cost.

5.2 Future Work

With respect to the work done in this thesis, the following modification could be done in future:-

- Problem can be solved by replacing series capacitor by a series connected Flexible AC Transmission Systems (FACTS) device. For a desired value of compensation, power injection model parameters of the compensating FACTS device can be evaluated.
- Instead of using Evolutionary Programming, any other Genetic algorithm based tool can be implemented.

APPENDIX A

IEEE 30 bus systm data:

LINE DATA

S.no	Bus from	Bus to	R(p.u)	X(p.u)	½(B) (p.u)	Tap ratio	MW flow limit
1	1	2	.01920	0.05750	.02640	1	1.3
2	1	3	.04520	0.18520	0.02040	1	1.3
3	2	4	.05700	0.17370	.01840	1	.65
4	3	4	.01320	0.03790	.00420	1	1.3
5	2	5	.04720	0.1830	0.02090	1	1.3
6	2	6	.05810	.17630	0.01870	1	.65
7	4	6	.01190	0.04140	0.00450	1	.9
8	5	7	.04600	.11600	0.01020	1	1.3
9	6	7	0.02670	0.08200	0.00850	1	1.3
10	6	8	0.01200	0.04200	0.00450	1	0.32
11	6	9	0.00000	0.20800	0.00000	1.01550	0.65000
12	6	10	0.00000	0.55600	0.00000	0.96290	0.32000
13	9	11	0.00000	0.20800	0.00000	1	0.65000
14	9	10	0.00000	0.11000	0.00000	1	0.65000
15	4	12	0.00000	0.25600	0.00000	1.01290	0.65000
16	12	13	0.00000	0.14000	0.00000	1	0.65000
17	12	14	0.12310	0.25590	0.00000	1	0.32000
18	12	15	0.06620	0.13040	0.00000	1	0.32000

19	12	16	0.09450	0.19870	0.00000	1	0.32000
20	14	15	0.22100	0.49970	0.00000	1	0.16000
21	16	17	0.08240	0.19320	0.00000	1	0.16000
22	15	18	0.10700	0.21850	0.00000	1	0.16000
23	18	19	0.06390	0.12920	0.00000	1	0.16000
24	19	20	0.03400	0.06800	0.00000	1	0.32000
25	10	20	0.09360	0.20900	0.00000	1	0.32000
26	10	17	0.03240	0.08450	0.00000	1	0.32000
27	10	21	0.03480	0.07490	0.00000	1	0.32000
28	10	22	0.07270	0.14990	0.00000	1	0.32000
29	21	22	0.01160	0.02360	0.00000	1	0.32000
30	15	23	0.10000	0.20200	0.00000	1	0.16000
31	22	24	0.11500	0.17900	0.00000	1	0.16000
32	23	24	0.13200	0.27000	0.00000	1	0.16000
33	24	25	0.18850	0.32920	0.00000	1	0.16000
34	25	26	0.25440	0.38000	0.00000	1	0.16000
35	25	27	0.10930	0.20870	0.00000	1	0.16000
36	28	27	0.00000	0.36900	0.00000	0.95810	0.65000
37	27	29	0.21980	0.41530	0.00000	1	0.16000
38	27	30	0.32020	0.60270	0.00000	1	0.16000
39	29	30	0.23990	0.45330	0.00000	1	0.16000
40	8	28	0.06360	0.20000	0.02140	1	0.32000

41	6	28	0.01690	0.05990	0.00650	1	0.32000

BUSDATA

Bus No.	Bus code	Voltage magnitude	Angle(in degrees)	Load (MW)	Load (Mvar)	Gen. (MW)	Gen. (Mvar)	Gen. (Qmin)	Gen. (Qmax)	Inj. Mvar
1	1	1.05	0	0	0	50	-30	0	150	0
2	2	1.033	0	21.7	12.7	20	-30	0	60	0
3	0	1.0	0	2.4	1.2	0	0	0	0	0
4	0	1.0	0	7.6	1.6	0	0	0	0	0
5	2	1.0058	0	94.2	19	15	-15	0	60	0
6	0	1.0	0	0	0	0	0	0	0	0
7	0	1.0	0	22.8	10.9	0	0	0	0	0
8	2	1.023	0	30	30	10	-15	0	50	0
9	0	1.0	0	0	0	0	0	0	0	0
10	0	1.0	0	5.8	2	0	0	0	0	19
11	2	1.0913	0	0	0	10	-10	0	-40	0
12	0	1.0	0	11.2	7.5	0	0	0	0	0
13	2	1.0883	0	0	0	12	-15	0	45	0

14	0	1.0	0	6.2	1.6	0	0	0	0	0
15	0	1.0	0	8.2	2.5	0	0	0	0	0
16	0	1.0	0	3.5	1.8	0	0	0	0	0
17	0	1.0	0	9	5.8	0	0	0	0	0
18	0	1.0	0	3.2	.9	0	0	0	0	0
19	0	1.0	0	9.5	3.4	0	0	0	0	0
20	0	1.0	0	2.2	.7	0	0	0	0	0
21	0	1.0	0	17.5	11.2	0	0	0	0	0
22	0	1.0	0	0	0	0	0	0	0	0
23	0	1.0	0	3.2	1.6	0	0	0	0	0
24	0	1.0	0	8.7	6.7	0	0	0	0	0
25	0	1.0	0	0	0	0	0	0	0	0
26	0	1.0	0	3.5	2.3	0	0	0	0	0
27	0	1.0	0	0	0	0	0	0	0	0
28	0	1.0	0	0	0	0	0	0	0	0
29	0	1.0	0	2.4	.9	0	0	0	0	0
30	0	1.0	0	10.6	1.9	0	0	0	0	0

COST COEFFICIENTS

c	B	a
0	2	.00375
0	1.75	.01750
0	1.00	.06250
0	3.25	.00834
0	3	.02500
0	3	.02500

GENERATION 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

EP PARAMETERS

S.No	EP Parameters	Value
1	Constant ap	0.95
2	Population size	20

VOLTAGE LIMITS

V (Min.)	V (Max.)
0	0
0	0
1.2	1.5
1.3	1.6
0	0
1.2	1.4
1.1	1.5
0	0
1.3	1.35
1	1.25
0	0
1.4	1.6
0	0
1.1	1.3
1	1.1
.9	1.2
1.2	1.3
1.3	1.5
1.4	1.6
1.1	1.3
1	1.7
1.3	1.6
1.2	1.4
1.1	1.3
1.4	1.5
1.3	1.5
1.3	1.4
1.2	1.4
1	1.3
1.5	1.6
1.9	1.5

ANGLE LIMITS

A (Min.)	A (Max.)
0	0
0	0
-45	45
-45	45
0	0
-45	45
-45	45

0	0
-45	45
-45	45
-45	45
-45	45
0	0
-45	45
-45	45
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