

Power System Optimization for Voltage Stability Improvement through Genetic Algorithm

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in

POWER SYSTEMS

by

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CERTIFICATE

I hereby certify that the work which is being presented in the dissertation entitled, **Power System Optimization for Voltage Stability Improvement through Genetic Algorithm** in the partial fulfilment of the requirement for the award of the Degree of *Master of Engineering* in **Power Systems** and submitted in the *Electrical & Instrumentation Engineering Department* of the **THAPAR UNIVERSITY** is an authentic record of my own work carried out under the supervision of **Dr. Sanjay K. Jain**, Associate Professor, EIED.

The matter presented in this dissertation has not been submitted for the award of any other degree of this or any other University.


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Abstract

The demand of electrical energy is continuously increasing and therefore it becomes difficult to operate the system securely while simultaneously having optimal cost of operation. The security of the system can be measured by voltage stability index (VSI), the voltage stability is formulated as L-index and its minimization is attempted for voltage secure operation. The optimal economy has been attempted by cost minimization various other aspects of minimization are minimization of Losses and minimization of emission resulting due to operation of thermal plants.

The above optimization has been attempted using genetic algorithm. For multi-objective optimization, fuzzy decision making is integrated into Genetic Algorithm. The objective are mapped into fuzzy memberships and optimization of membership function is attempted. The multi-objective optimization is attempted for minimization of L-index and Cost, Cost and Emission, L-index and Emission, L-index and loss, loss and cost. The result are also examine for three variables sets and four variables sets.

The algorithm is tested on IEEE 6-generator 30-bus and IEEE 7-generator 57-bus systems and the respective result is obtained.

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Nomenclature

B_{ij}	Susceptance of transmission line connected between i_{th} and j_{th} bus
g_k	Conductance of the K_{th} line
G_{ij}	Conductance of transmission line connected between i_{th} and j_{th} bus
L_j	L-index for the j_{th} node
N	Number of buses
N_C	Number of capacitor banks
N_g	Number of generator unit
N_{PQ}	Number of load buses
N_{tran}	Number of tap-setting transformer branches
N_{line}	Number of transmission line
N_{PV}	Number of voltage buses
P_{gi}	Generated active power at bus i
P_i	Real power injection of i_{th} bus
P_s	Real power generation of slack bus
Q_i	Reactive power injection of i_{th} bus
Q_{ci}	Reactive power generation of i_{th} capacitor bank
S_i	Line flow
t_k	Tap setting of transformer at branch k
V_i	Voltage magnitude of the i_{th} generator bus
V_j	Voltage magnitude of the j_{th} generator bus
θ_{ij}	Phase angle between the i_{th}, j_{th} unit
δ_i	Voltage phase angle of the i_{th} unit
δ_j	Voltage phase angle of the j_{th} unit

INTRODUCTION

1.1 OVERVIEW

The electric power industries are continuously growing from several decades, and this growth is necessary for fulfilling the demands of the consumers. The main purpose of these industries is to supply the electricity to the consumers at low price with high quality, reliability and without violating their constraints. As the demand is increasing day by day, load on generation, transmission, distribution systems is also increasing. Therefore, it becomes difficult to operate the system securely. If these systems operate adequately and securely then the systems stability is maintained. To retain the systems stability it is necessary to preserve the voltage at all buses in the systems close to its nominal value at all the times. The ability of a power system to maintain acceptable voltage is regarded as voltage stability problem. If the voltage move out too much from their nominal value, it is known as voltage collapse.

Voltage stability problem is taken as a reactive power optimization problem because it arises from the deficiency of reactive power. Due to voltage stability problem, there is always a possibility for the occurrence of severe blackouts in different parts of the system. Table 1.1 groups several known incidents and their time frame.

Electricity is continuously required for industrial, commercial and domestic purpose, so the aftereffects of blackouts can be understood easily. Thats why it is necessary to study the voltage stability in power system.

The nearly 70% of the total power is generated through the thermal power plants. The main emissions from coal fired and lignite from the thermal power plants are CO_2 , NO_x , SO_x , and air-borne inorganic particles such as fly ash, carbonaceous material (soot), suspended particulate matter (SPM), and other trace gas species. These pollutants disturb the whole natural

Table 1.1 Voltage collapse incidences

DATE	LOCATION	PEOPLE AFFECTED (MILLIONS)
31 July 2012	India	670
30 July 2012	India	330
10-11 Nov 2009	Brazil, Paraguay	87
18 Aug 2005	Indonesia	100
28 Sep 2003	Italy, Switzerland, Austria, Slovenia, Croatia	55
14-15 Aug 2003	The United States, Canada	55
02 January 2001	India	230
11 March 1999	Brazil	97
9 Nov 1965	Canada, The United States	30

cycle and therefore it is necessary to take a amended steps in order to reduce the pollutants but without effecting the generation capacity of the power industries. The fuel switches or gas cleaner, etc. are sometimes used to reduce the pollutants

In optimal power flow problem the main objective is to minimize the generation cost of power industries while satisfying the equality (power balance) and inequality (network constraint) constraints. Minimization of the emission by the equipments mentioned above is not economical. Therefore, for reducing the pollutant level, the minimization of the emission is also an important objective. Pollutants reduced by power dispatch approach is an efficient and economic option. Therefore, the optimal power dispatch considering emission besides cost minimization has received widespread attention with smaller capital outlay [1], [2], [3]. In other way, optimal power dispatch is preferable for pollutant level minimization because it can be implemented easily as well as it is less costly.

Nowadays electrical business has become the part of the deregulated environment therefore, there is a lot of competition between all power industries. All the industries are trying to provide electric power which is more reliable and highly qualitative. This can be obtained by reducing the losses in the transmission line networks. Reduction in transmission line losses will improve the power quality as well as reduces the cost of generation and maintenance

which ultimately lead to increase in customer satisfaction. In order to achieve this, active power transmission loss is taken as a objective function which can also help in system security and reduction in generation cost.

The optimal power flow was first discussed by Carpentier in 1962 [4] where the real and reactive power of generators is allowed to vary within certain limits for minimization of fuel cost. This is called as Optimal Power Flow (OPF) problem [5]. The OPF is multi-modal and highly non-linear optimization problem and is used to optimize the power solution of large power system. OPF help in different ways such as security improvement, voltage control, cost minimization, loss reduction. In the prior time, Gradient Methods such as Jacobian Method, Linear Programming Method, Non-linear Programming Method, Interior Point Method, Quadratic Programming Method, Gauss Seidal Method, Newton Raphson Method, are used to solve Optimal Power Flow Problems. But these methods are complex and sometime have convergence problem. Because of these difficulties advance Artificial Intelligence Methods are considered in place of prior conventional methods.

In this thesis Genetic Algorithms is used for solving optimal power flow problem in which active generated power, magnitude of generator voltages, transformer tap settings and switchable VAR sources are taken as a control variables. These problems are taken separately as single objective optimization problem and then in combination as a multi-objective optimization problem. This multi-objective problem has been solved by fuzzy-Genetic approach.

1.2 LITERATURE REVIEW

In the past decade, there have been several approaches to the optimal power flow. The generalized formulation of the power flow problem was introduced by Carpentier et al. [4] by including voltage, power flow and other important operating constraints. This formulation is known as optimal power flow (OPF) [6]. At the present era, the requirement is to design the system that fulfills various requirements without violations of the system limits. It is difficult to achieve this by conventional Newton Raphson or Gradient adjustment methods because of certain limitations. Such problems are overcome by the artificial intelligence techniques.

Optimization is a procedure of finding and comparing feasible solutions until no better solution can be found. An optimization problem with one objective function is known as Objective Optimization. Optimization problem with more than one objective function, the task of finding one or more optimum solution is known as multi-objective optimization [7].

Dommel and Tinney [8] proposed realistic method for solving the power flow problem by considering real and reactive power and transformer ratio are treated as control variable for minimizing the instantaneous cost and loss.

Hu and Wee [9] have considered minimization of emission over cost minimization. The emission was treated as constraints [10]. The conventional methods have some disadvantage such as insecure convergence, and even fail to converge due to inappropriate initial conditions for a Newton based method, cost approximation problem arise in piecewise quadratic. Chen and Chen [11] have using Lagrangian relaxation method for solving environmentally constrained economic dispatch (ECED) problem. where NO_x and SO_x are consider as constraints. The algorithm was used for handling both linear and non-linear problem.

Reid and Hasdorff [12] have described economic load dispatch problem as quadratic programming problem, and there is need of penalty factor and determination of gradient step size in this algorithm which can create convergence difficulties.

Tiranuchit and Thomas [13] have proposed the minimum singular value of the Jacobian of the load flow equation as a security index. Security index means the voltage stability index. The sensitivity of the voltage stability index together with accuracy in numerical computation is used for tracking the voltage related problem. Linearization approximation is used to identify the VAR support for maintaining the voltage profile in buses.

Bansilal et al. [14] have introduced a non-linear least squares optimization algorithm for voltage stability assessment. Kessel and Glavitsch [15] used the indicator L-index as voltage stability assessment for online testing of power system based on load flow. Carpentier et al. [4] used L-index for computation of optimal power flow.

Thukaram et al. [16] have presented a method for computation of static collapse proximity based on optimal load flow. They considered the analysis of steady state voltage stability and propose the reactive power dispatch algorithm for voltage stability improvement.

Nanba et al. [17] have describe two control methods for improving voltage stability based on the concept of Voltage Instability Proximity Index (VIPI). In the first method Successive Quadratic Programming method was used to maximize the value of VIPI to find the optimal controls under various system conditions. In second method, evaluating the controls were used for maintaining the specified threshold value.

Tare and Bijwe [18] have introduced index based on the angle between real and reactive power gradient vectors of load buses. The algorithm is used to solve the indices that are used for improving the voltage stability limit. The minimization of the objective function implies the maximization of the index of that particular bus thus the load ability limit was enhanced.

Raghunatha et al. [19] have proposed sequential primal dual LP algorithm for improving the static voltage stability margin. The algorithm improved the system static voltage stability by minimizing the voltage stability index.

Choube et al. [20] have used linearized incremental model, for minimization of reactive power injection. When voltage stability index is enhanced than load bus voltage increases significantly. Linear programming methods have some disadvantages with the piecewise linear cost approximation [21].

When an optimization problem involves more than one objective function, the task of finding one or more optimum solution is known as multi-objective problem [22]. Since classical search and optimization algorithms use a point by point approach, the outcome of using a classical approach is a single optimized solution. When active power is dispatchable from the power system then generation cost is minimized and active power loss is minimized when only reactive power is dispatchable [23].

In [24], the usage of evolutionary computation techniques in their related field are given. Genetic algorithm was used for solving the reactive power Optimization problems. In [25] genetic algorithm approach was used for the voltage stability enhancement. Carpentier et al. [4] described Enhanced genetic algorithms (EGA) for solving the optimal power flow (OPF) with both continuous and discrete control variables. Unit active power outputs and generator-bus voltage magnitudes was considered as continuous control variables, transformer tap settings and switchable shunt devices discrete control variables. Branch flow limits, and load bus voltage magnitude limits are operating Constraints and generator reactive capabilities are included as penalties in the GA. Younes et al. [26] used a simple Genetic Algorithm for solving the OPF problem of the large distribution system.

Varadarajan and Swarup [27] have proposed differential evolutionary optimization algorithm for solving the reactive power dispatch. The cost, emission, power loss minimization, voltage profile improvement and voltage stability enhancement these are considered as objective functions. Numnonda and Annakkage [28] used GA for solving the optimal power dispatch problem for multi mode auction market. In this case total participant's welfare are maximized with network flow and transport limitation is considered as constraints.

In coordination with the optimal reactive power flow (ORPF) and continuation power flow (CPF) multi-objective optimization can be achieved with voltage security at an acceptable level [29]. Both losses and payment are minimized for the reactive power service.

1.3 OBJECTIVE OF THE WORK

The work in this dissertation has been carried out with the objective of studying the effect on VSI, generating cost, fuel emission and transmission loss by changing the number of control variables sets and compare its effectiveness with the base case power flow solution. The use of real power generation, generator voltages, the transformer tap changers and the switchable VAR sources as the control variables shall be explored. The optimization shall be carried out using genetic algorithms for single and fuzzy-GA for multi-objective optimization and their effectiveness be validated on standard test systems.

1.4 ORGANISATION OF THE THESIS

The dissertation has been organized into five chapters. The **Chapter 1** includes the brief overview, Literature review, objectives of the work and organization of the thesis. The **Chapter 2** describe the problem formulation i.e., L-index, generation cost, fuel emission and Loss with equality, inequality and aggregated objective function. The **Chapter 3** explain the complete theory of genetic algorithm, its implementation for problem solving and results of single-objective function. The **Chapter 4** discuss the Fuzzy decision making approach and its implantation with Genetic Algorithm and results of their application in multi-objective OPF problem. The **Chapter 5** summarizes the conclusions and future scope of work.

MATHEMATICAL FORMULATION OF OPTIMIZATION PROBLEMS

L-index(VSI), Generation Cost, Fuel Emission, Transmission Loss are solved to obtain the optimal value of generating voltage, transformer taps setting, reactive power generation, and active power generation in generating unit in order to obtain an economic and secure system. The formulation of these problems is discussed in this chapter.

2.1 VOLTAGE STABILITY ENHANCEMENT

Static and dynamic factor both are involved in the voltage stability analysis. For stability assessment control static approach is preferred in comparison to dynamic approach as dynamic approach is time consuming, therefore it is not recommended. Static analysis used for determination of index called voltage stability index. These indexes measure the closeness of system to voltage collapse. L-index is proposed in [15] as an index for calculating the closeness of the system to voltage collapse with the help of load flow analysis. Its value is varying between 0 (no-load) to 1(voltage collapse). The bus which has the highest value of L-index will be the most vulnerable buses in the system and priors to voltage collapse. The objective function VSI can be calculated as [21]:

$$F_1(x) = \text{Minimize}(L^{max}) \quad (2.1)$$

L-index for jth node is given by [21]:

$$L_j = \left| 1 - \sum_{i=1}^{N_g} F_{ji} \frac{V_i}{V_j} \angle(\theta_{ij} + \delta_i - \delta_j) \right| \quad (2.2)$$

Here,

$$F_{LG} = -[Y_{LL}]^{-1}[Y_{LG}] \quad (2.3)$$

$$\begin{bmatrix} I_G \\ I_L \end{bmatrix} = \begin{bmatrix} Y_{GG} & Y_{GL} \\ Y_{LG} & Y_{GG} \end{bmatrix} \begin{bmatrix} V_G \\ V_L \end{bmatrix} \quad (2.4)$$

where,

$F_1(x)$ = Voltage stability index i.e L-index,

V_i, V_j = voltage magnitude of the i_{th} and j_{th} generator buses,

θ_{ij} = phase angle of the i_{th}, j_{th} unit,

δ_i, δ_j = voltage phase angle of i_{th}, j_{th} units.

Here, the objective is the minimization of the maximum value of the L-index through rescheduling the reactive power control variables which satisfied all constraints.

2.1.1 Equality Constraints

The power flow equations are used as equality constraints [21] in OPF cases:

(i) Real power balance equation:

$$P_i - V_i \sum_{j=1}^N V_j [G_{ij} \cos \delta_{ij} + B_{ij} \sin \delta_{ij}] = 0; \quad i = 1, 2, \dots, (N - 1) \quad (2.5)$$

(ii) Reactive power balance equation:

$$Q_i - V_i \sum_{j=1}^N V_j [G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij}] = 0; \quad i = 1, 2, \dots, N_{PQ} \quad (2.6)$$

2.1.2 Inequality Constraints

The inequality constraints of the OPF reflect the limits on physical device in the power systems as well as the limits created to ensure the system security. The most usual types of inequality constraints are upper and lower limit on load bus voltage, upper and lower limits on real power generation in generators buses, maximum line loading limits and limits on tap settings. The inequality constraints on the problem variables considered include [21].

(i) Slack bus real power generation limits:

$$P_{gi}^{min} \leq P_{gi} \leq P_{gi}^{max}; \quad i = 1, 2, \dots, N_{gen} \quad (2.7)$$

P_{gi}^{min} and P_{gi}^{max} are minimum and maximum value of active power of the i_{th} bus respectively.

(ii) Generation reactive power generation limit:

$$Q_{gi}^{min} \leq Q_{gi} \leq Q_{gi}^{max}; \quad i = 1, 2, \dots, N_{gen} \quad (2.8)$$

Q_{gi}^{min} and Q_{gi}^{max} are respectively minimum and maximum value of reactive power at generation buses.

(iii) Generation bus voltage limit:

$$V_{gi}^{min} \leq V_{gi} \leq V_{gi}^{max}; \quad i = 1, 2, \dots, N_L \quad (2.9)$$

V_{gi}^{min} and V_{gi}^{max} are respectively minimum and maximum value of voltage at buses. N_L is the load buses.

(iv) Capacitor bank reactive power generation limit:

$$Q_{ci}^{min} \leq Q_{ci} \leq Q_{ci}^{max}; \quad i = 1, 2, \dots, N_{cap} \quad (2.10)$$

Q_{ci}^{min} and Q_{ci}^{max} , respectively are the minimum and maximum value of capacitor bank reactive power generation.

(v) Transformer tap setting limit:

$$t_k^{min} \leq t_k \leq t_k^{max}; \quad i = 1, 2, \dots, N_{tran} \quad (2.11)$$

t_k^{min} and t_k^{max} , respectively are the minimum and maximum value of tap setting in transformer.

(vi) Line flow limit:

$$S_i \leq S_i^{max}; \quad i \in N_1 \quad (2.12)$$

2.1.3 Aggregated Objective Function

The penalty factor method is utilised for handling the inequality constraints. In this regard, each control vector which violates the constraints will be fined by these penalty factors therefore in the next step this control vector will be deleted automatically. The inequality constraints are the control variables and all are considered in problem formulation and the constraints on the state variables are considered by adding a quadratic penalty function to the objective function. By adding the penalty function the new objective function becomes:

$$Min f = F(X) + SP + \sum_{j=1}^{N_{PQ}} VP_j + \sum_{j=1}^{N_g} QP_j + \sum_{j=1}^{N_l} LP_j \quad (2.13)$$

Where,

SP = reference bus generator active power limit violation.

VP_j = load bus voltage limit violation.

QP_j = reactive power generation limit violation.

LP_j = line flow limit violation. These factor are defined as:

$$SP = \begin{cases} K_s(P_s - P_s^{max})^2 & : P_s > P_s^{max} \\ K_s(P_s - P_s^{min})^2 & : P_s < P_s^{min} \\ 0 & : otherwise \end{cases}$$

$$VP_j = \begin{cases} K_v(V_j - V_j^{max})^2 & : V_j > V_j^{max} \\ K_v(V_j - V_j^{min})^2 & : V_j < V_j^{min} \\ 0 & : otherwise \end{cases}$$

$$QP_j = \begin{cases} K_q(Q_j - Q_j^{max})^2 & : Q_j > Q_j^{max} \\ K_q(Q_j - Q_j^{min})^2 & : Q_j < Q_j^{min} \\ 0 & : otherwise \end{cases}$$

$$LP_j = \begin{cases} K_l(L_j - L_j^{max})^2 & : L_j > L_j^{max} \\ 0 & : otherwise \end{cases}$$

where K_s, K_v, K_q and K_l are the penalty factors. Effectiveness of the penalty function depends on the selection of the values of penalty factor.

2.2 GENERATION COST MINIMIZATION

In the OPF formulation minimization of the total real power generation cost is most commonly used. The individual cost of each unit is calculated which are represented in quadratic curves of

the second order. After that sum of the quadratic cost model of each generator unit gives the objective of the entire power system [30].

$$\text{Min}F_2(X) = \sum_{i=1}^{N_g} a_i P_{gi}^2 + b_i P_{gi} + c_i \quad i = 1, 2, \dots, N_g \quad (2.14)$$

Where,

$F_2(X)$ = Total Generation cost (\$/h),

N_g = Number of generating unit including slack bus,

P_{gi} = Generated active power at bus i ,

a_i, b_i, c_i = Generation constant coefficient of the i_{th} unit.

The equality and inequality equation are same as in section 2.1.

2.3 FUEL EMISSION MINIMIZATION

The emission function can be a sum of all types of pollutants/emissions such as NO_2, SO_2, CO_2 , thermal emission, etc. In this study, only two types of emission are considered which are mostly occurring in large quantity in comparison to other pollutants i.e. NO_2, SO_2 . The amount of NO_2 and SO_2 emission from the generator output is obtained by the sum of a quadratic and exponential function which are as follows [30]:

$$\text{Min}F_3(X) = \sum_{i=1}^{N_g} (\gamma_i P_{gi}^2 + \beta_i P_{gi} + \alpha_i + \zeta_i \exp(\lambda_i P_{gi})) \quad (2.15)$$

where,

$F_3(X)$ = Total emission(ton/h),

$\gamma_i, \beta_i, \alpha_i, \zeta_i$ and λ_i = The emission coefficients of the i_{th} unit.

The equality and inequality equation are same as in section 2.1.

2.4 TRANSMISSION LOSS MINIMIZATION

The objective is to minimize the total active power losses in the transmission line. This can be evaluated as :

$$F_4(X) = \sum_{k=1}^{N_{line}} g_k [V_i^2 - V_j^2 - 2V_i V_j \cos(\delta_i - \delta_j)] \quad (2.16)$$

Where,

$F_4(X)$ = transmission loss(MW),

N_{line} = number of transmission lines,

g_k = the conductance of the K_{th} line,

V_i and V_j = the voltage magnitude at the end buses i and j,

δ_i and δ_j = the voltage phase angle at the end buses i and j.

SINGLE-OBJECTIVE OPTIMIZATION USING GENETIC ALGORITHM

3.1 GENETIC ALGORITHM

Genetic Algorithm is population- based optimization approach. Some changes have been made in the original Binary- coded GA for improving the capability of GA to solve the reactive power dispatch problem. Firstly the decision variables in the chromosomes are represented in real and integer value instead of binary strings. Chromosomes are represented in that form has some advantage over binary coding. The efficiency of the GA is increased so, there is no need of converting binary to decimal and vice-versa (i.e., no Hamming cliff problem) and less memory space is required. The evaluation and selection process are same as binary-coded GA but crossover and mutation are modified. The details of the operators used in proposed GA are presented below:

3.1.1 Initialization

Generate initial value for each chromosome in the population randomly. Each chromosome has 19 genes and 30 chromosomes which forms the population in case of 30-bus 4 variable. In each chromosome there are five genes of active power generation, five genes of generator bus voltage magnitude, four genes of transformer tap position and five genes of switchable VAR sources. For each chromosome the Newton Raphson power flow is executed. From the results of power flow solutions, obtain the dependent and independent variables while verifying all the constraints are within the limits. The generator voltages vary within the range of 0.95 to 1.05 p.u., the transformer tap settings varies within the range of 0.9 to 1.1 p.u. with a step size of 0.025 p.u. and the switchable VAR sources vary within the range of 1 to 5 with a step size of 1 p.u. The generator active power and generator bus voltages are represented as floating point numbers, whereas the transformer tap position and the reactive power generation of capacitor

bank are represented as integers.

$$X = [P_g, V_g, TAP, Q_c]_{1 \times n} \quad (3.1)$$

$$P_g = [P_{g1}, P_{g2}, \dots, P_{g(N_{gen}-1)}]_{1 \times (N_{gen}-1)} \quad (3.2)$$

$$V_g = [V_{g1}, V_{g2}, \dots, V_{gN_{gen}}]_{1 \times N_{gen}} \quad (3.3)$$

$$TAP = [TAP_1, TAP_2, \dots, TAP_{N_{tran}}]_{1 \times N_{tran}} \quad (3.4)$$

$$Q_c = [Q_{c1}, Q_{c2}, \dots, Q_{cN_{cap}}]_{1 \times N_{cap}} \quad (3.5)$$

$$n = (N_{tran} + N_{cap} + N_{gen} + (N_{gen} - 1)) \quad (3.6)$$

where,

P_{gi} = Real power generation of the i_{th} generator,

V_{gi} = Voltage magnitude of the i_{th} generator,

TAP_i = Tap of the i_{th} transformer,

Q_{ci} = Reactive power of the i_{th} compensator capacitor.

3.1.2 Selection Operator

From the values of dependent and independent variables the objective functions are calculated. Based on the results of objective function, the chromosomes are arranged in ascending order. Reproduction (selection) operation is applied. Selection is the process in which individual strings are copied according to their objective function. Selection passes the best solution and eliminates the bad/unfitted solutions but population size is kept constant. The best solutions are emphasized for achieving the goal of the fittest individual to be selected for reproduction. There are various numbers of reproduction operators in GA:

- Tournament Selection
- Ranking Selection
- Roulette Wheel Selection

Tournament selection is used here. So, tournament is played between two solutions and the better solution is chosen and placed in the mating pool [7]. Process continues and filled all the slots of mating pool with the better solution. It is the most popular selection method due to its simplicity.

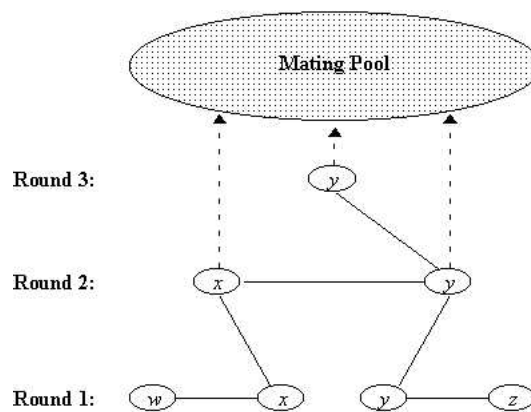


Fig. 3.1 Illustration of Tournament selection

3.1.3 Crossover Operator

In crossover operation two parents are selected from the parent pool randomly and perform crossover operation. Crossover is responsible for global search property of GA, because new chromosomes are produced here. For new chromosomes production, information is exchanged between two strings of the mating pool and new strings are produced. Here real and integer variables are considered instead of the binary so, each chromosome in the population consist of two types of variable; real and integer. Firstly the two types chromosomes are cut at the boundary between the float and integer variables. Then separate crossover is applied for real and integer value. Two - point crossover are applied for integer value as shown in Fig 3.2 and blend crossover operator (BLX- α) are applied for real variable. The blend crossover operator is based on the theory of interval schemata that was introduced by Eshelman and Schaffer (1993) is employed in the study of real variables.

For the values u_i^j and u_i^k of the variable u_i in the parents j and k, BLX- α operator creates new points uniformly at random from a range extending an amount $\alpha|u_i^{(j)} - u_i^{(k)}|$ on either side of the region bounded by the parents [21]. Fig 3.2 shows the BLX- α crossover operation in one dimensional case. u_1 and u_2 represent the two parents for a particular variable. The value of off springs e_1 and e_2 are :

$$e_1 = u_1 - \alpha I \quad (3.7)$$

$$e_2 = u_2 - \alpha I \quad (3.8)$$

where, $I = u_2 - u_1$

e_1 and e_2 will lie between u_{min} (lower bound) and u_{max} (upper bound). $\alpha = 0.5$ provide good

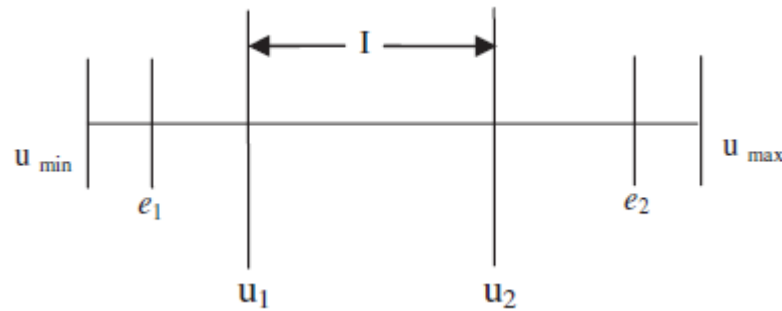


Fig. 3.2 Schematic representation of BLX- α crossover

result in number of test problems. One of the important features of blend crossover is that it depends on the location of the parents. If both are close to each other than new point is also close/similar to parents. Otherwise the search is more like a random search.

3.1.4 Mutation Operator

Mutation operator is the process in which a new genetic material is injected in the population. It is like a background operator because it play dominant role in the evolutionary process. Mutation randomly alters the variable with small probability. As in crossover, separate crossover is applied for real and integer variable same is in mutation. If the selected number in the mutation process is real then Uniform mutation is applied in that case and the number is replace by the uniform number between the variables lower and upper bound. Otherwise, applying the boundary mutation, which can replace the selected integer variable with its boundary limits.

3.1.5 Termination Condition

This generational process is repeated until a termination condition has been reached. Genetic Algorithm is terminated when reached the fixed number of generations.

3.2 IMPLEMENTATION VOLTAGE STABILITY IMPROVEMENT THROUGH GENETIC ALGORITHM

The procedure for the implementation of the Genetic algorithm is as follows:

Step1: Read test system bus data, line data, generation constant coefficient, (a_i, b_i, c_i) , and emission coefficient $(\gamma_i, \beta_i, \alpha_i)$.

- Step2:** Initialize suitable Generation limit, Population size, Problem dimension, Crossover Probability, Mutation Probability.
- Step3:** Check the limits of the initially generated population and all the genes in the chromosomes of population.
- Step4:** Replace the control variables (i.e. Generated voltage, Transformer tap setting, real and reactive power) by the respected genes in each chromosomes of the population.
- Step5:** Solve the power balance equation 2.5, 2.6 by using changed control variables. In this, Y_{bus} and load flow is calculated. From the results of power balance solutions obtain the dependent and independent variables.
- Step6:** Evaluate the objective function by using the equation (2.1, 2.14, 2.15, 2.16) of each chromosome in the population for the base case solution with the help of independent variable (i.e. Y , Voltage, P_g).
- Step7:** Apply the tournament selection operation between two parents as discussed in previous section(3.1.2) and again arrange the population according to the operation performed.
- Step8:** Apply the crossover and mutation as discussed earlier and generate new population.
- Step9:** Using new population replace the control variable again(i.e. Real power generation, Generated voltage, Transformer tap setting, reactive power) by the respected genes in each chromosomes of the population.
- Step10:** Again solve the Power balance equation and evaluate the objective function of each chromosome in the population and examine that any dependent and independent variable are not crossing their limit by using equation(2.7- 2.12).
- Step11:** If any of dependent and independent variable are violating their limit then penalty factor is added to the objective function as given in equation(2.13).
- Step12:** Stop and return the best solution, if the end condition is satisfied.
- Step13:** Otherwise go to step 7.
- Step14:** Find the optimized value and respective value of another objective function.

3.3 30-BUS SYSTEM ANALYSIS

The optimization problem solved by Genetic algorithm is carried out on 30-bus system whose data is given in APPENDIX-I. The Generation limits, Generation constant coefficient and Emission coefficients are also given in APPENDIX-I. The IEEE 30-Bus system has six generators, 24 load buses and 41 transmission lines of which four branches (6-9), (6-10), (4-12) and (28-27) are with the tap changing transformer. The load flow analysis are summarized in Table 3.1, 3.2 and respective value of L-index, generation cost, fuel emission and transmission loss are also given for the base load case. From this computation it is found that $L^{max} = 0.092369$ and the five weakest buses (24, 25, 26, 29 and 30) are selected whose L-index value are high. These five buses has been selected for reactive power injection.

3.3.1 Case-I : Three Control Variables Sets

The problem is formulated with three control variables i.e. generator voltages (V_g) whose voltage magnitude limits is between 0.95 p.u. to 1.1 p.u., the transformer tap changers(t_k) whose value is between 0.9 p.u. to 1.1 p.u. and the switchable VAR sources(Q_c) which is always kept within the range of 1 p.u. to 5 p.u. The proposed Genetic algorithm has been used for solving optimization problem. The result of applying genetic algorithm are given in Table 3.1 and Fig 3.3a shows the improvement in voltage profile before and after optimization.

3.3.1.1 Optimization for L-index Minimization

In this case study, developed algorithm has been applied for single objective i.e. L-index minimization. The optimization result and the corresponding setting of the control variables are given in Table 3.1 and respective value of the another objective functions are also shown there. In this case, the objective is to minimize the L-index and it can be easily seen from the given Table 3.1 that the L-index after Load Flow is 0.092369 and after applying OPF with GA is 0.049871 that means there is reduction of 46% in L-index.

3.3.1.2 Optimization for Generation Cost Minimization

The optimization results are obtained. The solutions after applying load flow using Newton Raphson as well as for Genetic algorithm based OPF are calculated and given in Table 3.1. As the objective is the minimization of generation cost, thus from Table 3.1 it is clear that after

applying Genetic algorithm based OPF the generation cost has been reduced evidently to 824.45 \$/hr which was 825.37 \$/hr earlier which is 0.11% less while solving it by Load Flow using Newton-Raphson method.

Table 3.1 Results of optimization using GA for IEEE 30-bus Three control variables set system

Control Variable	Load Flow Solution	L-index Minimized	Cost Minimized	Emission Minimized
V_2	1.03380	1.0710	1.0362	1.0423
V_5	0.98196	1.0012	1.0070	1.0381
V_8	1.02300	1.0364	1.0071	1.0151
V_{11}	1.03700	1.0204	1.0651	1.0543
V_{13}	0.98800	1.0547	1.0376	1.0447
t_1	0.97800	1.0750	1.0250	0.9500
t_2	0.96900	1.1000	0.9000	1.0750
t_3	0.93200	1.1000	1.0000	1.0000
t_4	0.96800	1.0000	1.0250	1.0000
Q_{24}	0.00000	5.0000	5.0000	5.0000
Q_{25}	0.00000	5.0000	1.0000	1.0000
Q_{26}	0.00000	5.0000	4.0000	3.0000
Q_{29}	0.00000	5.0000	1.0000	1.0000
Q_{30}	0.00000	5.0000	4.0000	3.0000
L-index	0.092369	0.049871	0.060671	0.059509
Cost (\$/hr)	825.37	827.75	824.45	832.9
Emission (ton/hr)	0.45488	0.45791	0.45373	0.45357

3.3.1.3 Optimization for Fuel Emission Minimization

The solutions after applying load flow using Newton Raphson as well as for GA based OPF are calculated for single-objective fuel emission and is given in Table 3.1. The Fuel Emission after

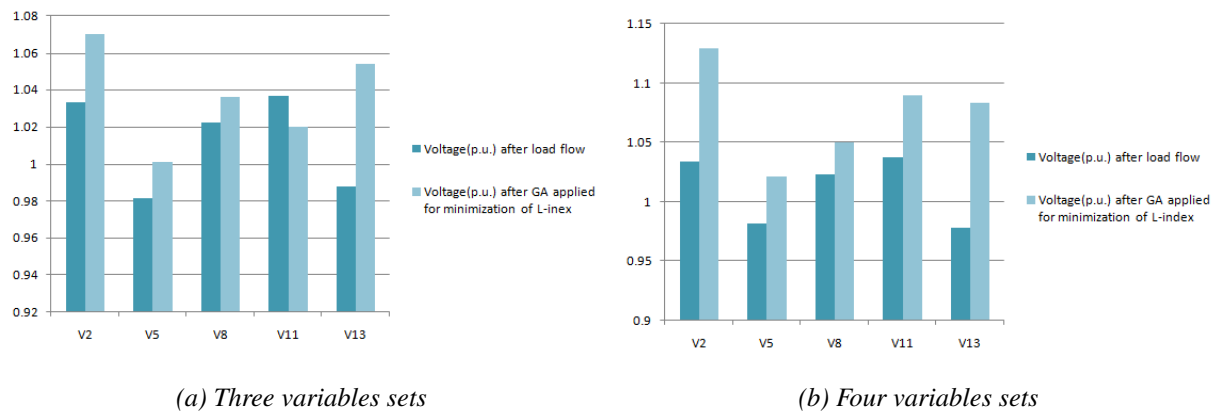


Fig. 3.3 Voltage profile before and after optimization for IEEE 30-bus system

Load Flow for base case is 0.45488 ton/hr and after applying OPF with GA is 0.45357 ton/hr that means there is reduction of 0.28% in Fuel Emission.

3.3.2 Case-II : Four Control Variables Sets

Four control variables are used in this case are real power generation(P_g), generator voltages (V_g), the transformer tap changers(t_i) and the switchable VAR sources(Q_c). The proposed Genetic algorithm has been used for solving optimization problems. The results of applying genetic algorithm are given in Table 3.2 and the improvement in the voltage profile before and after optimization are also shown in Fig 3.3b.

3.3.2.1 Optimization for L-index Minimization

In this case study, developed algorithm has been applied for single objective L-index minimization. The optimization results are obtained and are compared with the power flow solutions and are given in Table 3.2 and respective value of the another objective function and control variables setting are also shown there. In this case, the objective was to minimize the L-index. And it can be easily seen from the given Table 3.2, that the L-index after Load Flow is 0.092369 and after applying OPF with GA is 0.047995 that means there is a improvement of 48% in system security (L-index). This shows that the proposed algorithm is effective in reaching the optimal solution for the optimization problem.

Table 3.2 Results of optimization using GA for IEEE 30-bus Four control variables set system

Control Variable	Load Flow Solution	L-index Minimized	Loss Minimized	Cost Minimized	Emission Minimized
PG_1	2.3923	2.39580	1.87110	2.26370	1.75310
PG_2	0.5756	0.37925	0.63750	0.69251	0.74371
PG_5	0.2456	0.34441	0.42207	0.33047	0.42629
PG_8	0.3500	0.33603	0.34790	0.16934	0.35083
PG_{11}	0.1793	0.24966	0.24494	0.19862	0.24738
PG_{13}	0.1691	0.30856	0.34213	0.21476	0.33837
V_2	1.0338	1.12960	1.04030	1.03790	1.02590
V_5	0.9814	1.02170	1.01140	1.01550	0.99630
V_8	1.0230	1.05010	1.02300	1.00780	1.00100
V_{11}	1.0374	1.08970	1.01400	1.02970	0.99592
V_{13}	0.9881	1.08370	1.05330	1.02440	1.01350
t_1	0.9780	1.07500	0.92500	1.07500	1.05000
t_2	0.9690	1.00000	1.10000	0.92500	0.92500
t_3	0.9320	1.10000	1.02500	1.02500	1.10000
t_4	0.9680	1.00000	1.02500	1.00000	0.97500
Q_{24}	0.0000	5.00000	5.00000	2.00000	5.00000
Q_{25}	0.0000	2.00000	2.00000	1.00000	5.00000
Q_{26}	0.0000	5.00000	3.00000	5.00000	3.00000
Q_{29}	0.0000	5.00000	5.00000	5.00000	1.00000
Q_{30}	0.0000	5.00000	4.00000	2.00000	1.00000
L-index	0.092369	0.047995	0.067015	0.064035	0.06021
Loss (MW)	17.78600	22.43	12.394	17.074	12.486
Cost (\$/hr)	825.37	850.82	818.42	797.65	826.34
Emission (ton/hr)	0.45488	0.4496	0.32923	0.4227	0.30973

3.3.2.2 Optimization for Transmission Loss Minimization

In this case study, developed algorithm has been applied for single objective transmission cost minimization. The optimization results are obtained and are compared with power flow results as given in Table 3.2 and respective value of the another objective function are also shown there. In this case, the objective was to minimize the transmission cost. And it can be easily seen from the given Table 3.2 that the loss after load flow is 17.786 MW and after applying OPF with Genetic algorithm is 12.394 MW which is 30% less than the loss.

3.3.2.3 Optimization for Generation Cost Minimization

The results obtained after applying load flow and Genetic algorithm based OPF are summarized in Table 3.2 and respective value of another objective functions and the control variable settings are also shown there. The minimisation of the generation cost is considered as an objective function in this case. The Cost after Load Flow is 825.37 \$/hr and after applying OPF with GA is 797.65 \$/hr which is 3.5 % less in comparison to the load flow solution.

3.3.2.4 Optimization for Fuel Emission Minimization

The GA based algorithm for fuel emission Minimization is considered in this case. The load flow analysis and optimization result for this case are shown in Table 3.2 and the respective values of another objective function and control variable setting is also given there. The fuel emission after Load Flow for base case is 0.45488 ton/hr and after applying OPF with GA is 0.30973 ton/hr that means there is reduction of 31.9% in Fuel Emission.

For examination of voltage security improvement after applying Genetic Algorithm, a graph of the voltage profile of the system before and after the application of the algorithm are displayed in Fig 3.3 for IEEE 30-bus system. Improvement in the voltage profile of the system after the application of the algorithm is evident from this diagram.

3.4 57-BUS SYSTEM ANALYSIS

The optimization problem solved by Genetic algorithm is carried out on 57-bus system whose data is given in APPENDIX-II. It has 7 generators, 50 load buses, 5 synchronous condensers and 80 transmission lines of which 17 branches are with the tap changing transformer. The

voltage magnitude limits of all buses are set to 0.94 p.u. to 1.06 p.u. The load flow analysis are summarized in Table 3.3,3.4 and respective value of generation cost, L-index and transmission loss are given for the base case. From this computation it is found that $L^{max} = 0.13594$ and the five weakest buses(30,31,32,33 and 34) are selected whose L-index values are high. These five buses has been selected for reactive power injection.

3.4.1 Case-I : Three Control Variables Sets

Three control variable used in this case are generator voltages (V_g), the transformer tap changers(t_i) and the switchable VAR sources(Q_c). The proposed Genetic algorithm is used for solving optimization problem and the results are given in Table 3.3 and improvement in voltage profile is shown in Fig 3.4a.

3.4.1.1 Optimization for L-index Minimization

In this case study, developed algorithm has been applied for single objective i.e. L-index minimization. The optimization results are obtained and are compared with power flow results and respective value of the another objective value is also shown in Table 3.3. In this case, the objective was to minimize the L-index. And it can be easily seen from the given Table 3.3 that the L-index after Load Flow is 0.13594 and after applying OPF with GA is 0.10724 that means there is reduction of 21% in L-index .

3.4.1.2 Optimization for Transmission Loss Minimization

Here, the minimisation of the Transmission Loss of generation is considered as an objective function. The comparison between its load flow and optimized result is given in Table 3.3 and respective value of the another objective function and corresponding control settings are shown in Table 3.3. The losses after load flow is 28.738 MW and after applying OPF with GA is 22.193 MW which is 28 % less in comparison to the load flow solution.

3.4.1.3 Optimization for Generation Cost Minimization

Similar to the previous cases, the optimization results for generation cost minimization are obtained by using GA and are compared with power flow results as given in Table 3.3 and respective value of the another objective value is also shown there. It can be seen from the given

Table 3.3 that the cost after load flow is 12137 \$/hr and after applying OPF with GA is 12012 \$/hr that means there is reduction of 1.02% in cost.

Table 3.3 Results of optimization using GA for IEEE 57-bus Three control variables set system

Control Variable	Load Flow Solution	L-index Minimization	Loss Minimization	Cost Minimization
V_2	1.010	0.9835	1.0316	1.0378
V_3	0.985	1.0493	1.0393	1.0402
V_6	0.980	1.0490	1.0361	1.0324
V_8	1.005	1.0214	1.0162	1.0153
V_9	0.980	1.0561	1.0309	1.0291
V_{12}	1.015	1.0433	1.0488	1.0472
t_1	0.970	0.9000	0.9000	0.9600
t_2	0.978	1.1000	1.0800	0.9500
t_3	1.043	0.9000	1.0000	0.9000
t_4	1.000	0.9000	0.9000	0.9000
t_5	1.000	1.1000	0.9700	0.9000
t_6	1.043	0.9000	1.0400	1.0400
t_7	0.967	1.1000	1.1000	1.1000
t_8	0.975	1.1000	0.9900	0.9000
t_9	0.955	1.0800	1.1000	1.0700
t_{10}	0.955	1.1000	1.0600	1.0200
t_{11}	0.900	1.1000	1.0200	1.0000
t_{12}	0.930	1.1000	1.0500	1.0500
t_{13}	0.895	1.1000	1.0100	1.0000
t_{14}	0.958	1.1000	0.9100	1.0300
t_{15}	0.980	0.9200	1.0500	1.0500
t_{16}	0.940	0.9000	0.9000	0.9900
t_{17}	0.958	1.1000	1.1000	1.1000
Q_{30}	0.018	1.0000	1.0000	1.0000
Q_{31}	0.029	1.0000	1.0000	1.0000
Q_{32}	0.008	1.0000	1.0000	1.0000
Q_{33}	0.019	1.0000	1.0000	1.0000
Q_{34}	0.000	1.0000	1.0000	1.0000
L-index	0.13594	0.10724	0.12736	0.13776
Loss (ton/hr)	28.738	26.911	22.193	22.251

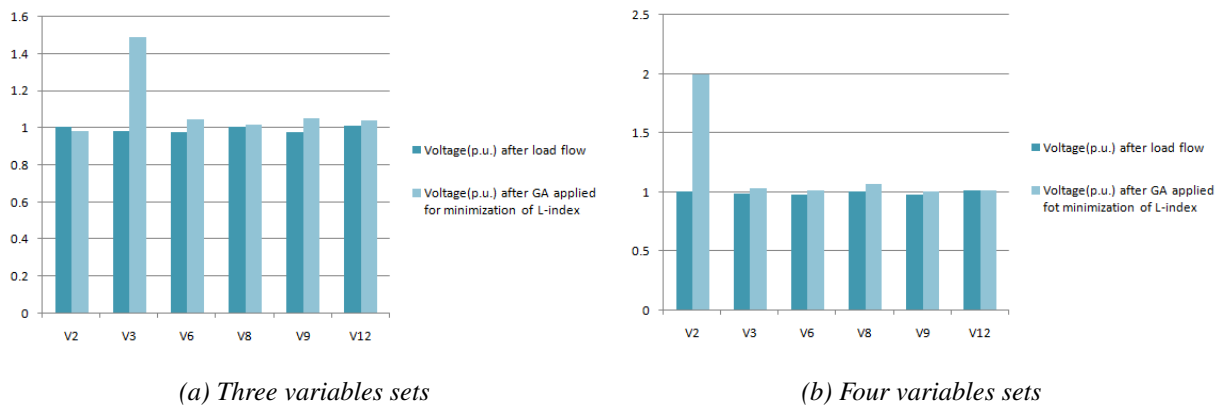


Fig. 3.4 Voltage profile before and after optimization for IEEE 57-bus system

Cost (\$/hr)	12137	12232	12232	12012
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3.4.2 Case-II : Four Control Variables Sets

Four control variable used in this case are real power generation(P_g), generator voltages (V_g), the transformer tap changers(t_i) and the switchable VAR sources(Q_c). The proposed Genetic algorithm is used for solving problem. The results of applying Genetic algorithm are given in Table 3.4 and Fig 3.4b shows the improvement in voltage profile before and after applying the optimization.

3.4.2.1 Optimization for L-index Minimization

In this case study, developed algorithm has been applied for single objective L-index minimization. The optimization results are obtained and are compared with the power flow results are given in Table 3.4. In the present case, our objective was to minimize the L-index and we can see from the Table 3.4 that the L-index after the power flow is 0.13594 but after the application of OPF with GA the L-index are reduced to 0.1213.

3.4.2.2 Optimization for Transmission Loss Minimization

In this case, the minimisation of the transmission loss is considered as an objective function. The comparison between its load flow and optimized results are given in Table 3.4 and respective value of the another objective function and corresponding setting of the control variable are

shown in Table 3.4. The Loss after Load Flow is 28.738 MW and after applying OPF with GA is 20.003 MW which is 3.4973 % less in comparison to the load flow solution.

3.4.2.3 Optimization for Generation Cost Minimization

Similarly as for the previous cases, developed algorithm has been applied for single objective i.e. generation cost minimization. The optimization results are obtained and are compared with power flow results are given in Table 3.4 and respective value of the another objective function are also shown there. In this case, the objective was to minimize the total generation cost. And it can be easily seen from the given Table 3.4 that the cost after load flow is 12137 \$/hr and after applying OPF with GA is 9339.6 \$/hr that means there is reduction of 23% in cost.

Table 3.4 Results of optimization using GA for IEEE 57-bus Four control variables set system

Control Variable	Load Flow Solution	L-index Minimization	Loss Minimization	Cost Minimization
PG_1	2.322	0.27562	0.11554	1.36830
PG_2	0.030	0.33462	0.31818	0.06156
PG_3	0.410	0.50470	0.01850	0.73819
PG_6	0.750	0.78745	0.86633	0.26597
PG_8	1.500	0.61526	0.97013	0.50416
PG_9	1.210	0.62465	0.80232	0.30299
PG_{12}	3.770	0.72814	0.77852	0.89756
V_2	1.010	0.99746	1.02830	1.01910
V_3	0.985	1.03040	1.01030	1.02070
V_6	0.980	1.01390	0.98763	1.01830
V_8	1.005	1.07420	0.96984	1.04810
V_9	0.980	1.00800	0.99513	1.01700
V_{12}	1.015	1.02020	0.99536	1.02690
t_1	0.970	0.90000	1.03000	1.07000
t_2	0.978	1.10000	0.94000	1.00000
t_3	1.043	0.90000	1.01000	0.93000
t_4	1.000	1.10000	1.00000	0.98000
t_5	1.000	1.10000	0.90000	1.10000
t_6	1.043	0.98000	0.98000	0.94000
t_7	0.967	1.09000	1.07000	0.97000
t_8	0.975	1.10000	0.90000	1.04000

t_9	0.955	1.10000	0.90000	0.96000
t_{10}	0.955	1.10000	1.06000	0.99000
t_{11}	0.900	1.10000	1.02000	1.09000
t_{12}	0.930	1.10000	1.08000	1.02000
t_{13}	0.895	1.08000	0.93000	0.92000
t_{14}	0.958	1.05000	0.90000	1.03000
t_{15}	0.980	0.95000	0.95000	1.06000
t_{16}	0.940	0.91000	0.90000	0.95000
t_{17}	0.958	0.99000	0.9900	0.90000
Q_{30}	0.018	1.00000	1.0000	2.0000
Q_{31}	0.029	1.00000	1.0000	3.0000
Q_{32}	0.008	1.00000	1.0000	1.0000
Q_{33}	0.019	1.00000	1.0000	4.0000
Q_{34}	0.000	1.00000	1.0000	5.0000
L-index	0.13594	0.1213	0.16295	0.16809
Loss (ton/hr)	28.738	26.611	20.003	37.117
Cost (\$/hr)	12137	11465	11924	9339.6

For examination of voltage security improvement after applying Genetic algorithm, a graph of the voltage profile of the system before and after the application of the algorithm are displayed in Fig 3.4 for the IEEE 57-bus system. Improvement in the voltage profile of the system after the application of the algorithm is evident from this diagram.

MULTI-OBJECTIVE OPTIMIZATION USING FUZZY-GENETIC ALGORITHM

4.1 MULTI-OBJECTIVE OPTIMIZATION

For economic and security point of view, the objectives are to optimize L-index, generating cost, emission and loss of the system simultaneously. As these objectives are conflicting in nature and difficult to optimize, the problem is solved by transforming the multi objective problem into a single objective problem with the help of a Fuzzy Decision Making approach. The multi-objective problem can be presented as:

Min /Max

$$F(x) = [f_1(x), f_2(x) \dots \dots f_k(x)] \quad (4.1)$$

Subjected to:

$$\text{constraint1} : h_k(x) = 0, k = 1, 2, 3 \dots \dots k \quad (4.2)$$

$$\text{constraint2} : g_j(x) \leq 0, j = 1, 2, 3 \dots \dots j \quad (4.3)$$

where, $f_1(x), f_2(x) \dots \dots f_k(x)$ are the objective functions. The objective can be maximum type or minimum type.

4.2 FUZZY DECISION MAKING

The fuzzy sets are defined by equations called membership functions. These functions represent the degree of membership in fuzzy sets using values from 0 to 1. The membership value 0 indicates incompatibility with the sets, while 1 means full compatibility. Fuzzy membership functions which assign a degree of satisfaction to each objective are defined based on which the best solution can be found out of the available optimal solutions.

Here, it is assumed that $\mu(F_i)$ is a strictly monotonic decreasing function defined as:

$$\mu(F_i) = \begin{cases} 1 & ; F_i \leq F_i^{min} \\ \frac{F_i^{max} - F_i}{F_i^{max} - F_i^{min}} & ; F_i^{min} < F_i < F_i^{max} \\ 0 & ; F_i \geq F_i^{max} \end{cases}$$

Where F_i^{min} and F_i^{max} are the expected minimum and maximum values of i^{th} objective function. The value of the membership function indicates how much (in scale from 0 to 1) a solution is satisfying the i^{th} objective F_i . For fuzzy multiple objectives, the fuzzy solution can be calculated as:

$$F(X) = \min[\mu_1(X), \mu_2(X)] \quad (4.4)$$

The maximum value of $F(X)$ is considered as the optimal solution.

4.3 APPLICATION OF THE FUZZY-GENETIC ALGORITHM TO THE MULTI-OBJECTIVE OPF

The general procedure for the implementation of the Genetic algorithm is as follows:

- Step1:** Read test system bus data, line data, generation constant coefficient, (a_i, b_i, c_i) , and emission coefficient $(\gamma_i, \beta_i, \alpha_i)$.
- Step2:** Initialize suitable generation limit, population size, problem dimension, crossover probability and mutation probability.
- Step3:** Check the limits of the initially generated population and all the genes in the population.
- Step4:** Replace the control variable (i.e. real power generation, generated voltage, transformer tap setting, reactive power) by the respected genes in each chromosomes of the population.
- Step5:** Solve the power balance equations 2.5, 2.6 by using changed control variables. In this, Y_{bus} and load flow is calculated. From the results of power flow solutions obtain the dependent and independent variables.
- Step6:** Evaluate the objective function by using the equation (2.1, 2.14, 2.15, 2.16) of each chromosome in the population for the base case solution.

Step7: Calculate fuzzy membership function of any of the two objective functions out of 4 objective functions with the help of independent variables (i.e. Y, volt, P_g) by using the formula.

$$\mu(F_i) = \begin{cases} 1 & ; F_i \leq F_i^{min} \\ \frac{F_i^{max} - F_i}{F_i^{max} - F_i^{min}} & ; F_i^{min} < F_i < F_i^{max} \\ 0 & ; F_i \geq F_i^{max} \end{cases}$$

Step8: Calculate the fitness value by selecting a minimum value from both of the two fuzzy membership function as 4.4. Sort the fitness function in descending order and arrange the population and two of the objective function according to the fitness function.

Step9: Apply the tournament selection operation between two parents as discussed in previous section 3.1.2 and again arrange the population and any two of the objective functions according to the operation performed.

Step10: Apply the crossover and mutation as discussed earlier and generate new population.

Step11: Replace the control variable (i.e. real power generation, generated voltage, transformer tap setting, reactive power) by the respected genes in each chromosomes of the population using new population.

Step12: Again solve the Power balance equation and evaluate the objective function of each chromosome in the population and examine that the dependent and independent variable are not crossing their limit by using equation(2.7- 2.12).

Step13: If any of dependent and independent variable are violating their limits then penalty factor is added to the objective function as given in equation(2.13).

Step14: Again calculate fuzzy membership function of same two objective functions by using the formula given in equations (2.1, 2.14, 2.15 and 2.16).

Step15: Calculate the fitness value by selecting a minimum value from both of the two fuzzy membership function as $\mu = [\max\{\min(\mu(F_i), (\mu(F_i)))\}]$.

Step16: Fitness function of that and previous objective are sorted and arrange the population and two of objective according with that.

Step17: Stop and return the best solution, if the end condition is satisfied

Step18: The maximization of $F(X)$ is considered as the objective.

Step19: Otherwise go to step 9.

Step20: Find the optimized value and respective value of another objective function.

4.4 30-BUS SYSTEM ANALYSIS

The load flow analysis and optimization results of the IEEE 30-Bus system are summarized in Table 4.1, 4.2 and the respective value of generation cost, fuel emission and L-index are given for the base case. From this computation it is found that $L^{max} = 0.092369$ and the five weakest buses are selected (24, 25, 26, 29 and 30) whose L-index values are high. These five buses have been selected for reactive power injection. The lower and upper voltage magnitude limits of all the generator buses are 0.95 p.u. and 1.1 p.u respectively.

4.4.1 Case-I : Three Control Variables Sets

Three control variables which are used in this case are generator voltages (V_g), the transformer tap changers(t_k) and the switchable VAR sources(Q_c). The proposed Fuzzy-Genetic algorithm is used for solving problems. The results of applying Fuzzy-Genetic algorithm are given in Table 4.1 and Fig 4.1 shows the variation in the values of the objective functions with each iteration.

4.4.1.1 L-index and Generation Cost Minimization

Fig 4.1a shows the optimization results obtained with L-index and generation cost minimization. The best compromise solution of L-index and cost minimization are 0.054598 and 824.77 \$/hr respectively, which is 40.89% and 0.07 % reduced from its base case. The results and corresponding setting of the control variables are shown in Table 4.1.

4.4.1.2 Generation Cost and Fuel Emission Minimization

With the simultaneous minimization of generation cost and fuel emission are discussed in this case, the best compromise solution are 824.52 \$/hr and 0.45381 ton/hr respectively, which is 0.102% and 0.235% reduced from its base case. The results and corresponding setting of the control variable are shown in Table 4.1 and Fig 4.1b shows the optimization results obtained with generation cost and emission minimization.

4.4.1.3 L-index and Fuel Emission Minimization

In this case study, developed algorithm has been applied for multi-objectives namely L-index and fuel emission. The optimization results obtained and the corresponding setting of the control variables are given in Table 4.1. The best compromise solution obtained are 0.049657 and 0.45386 ton/hr, which is 46.24% and 0.224% reduced from its base case. Correspondingly, the optimization results of applying Fuzzy-Genetic algorithm is shown in Fig 4.1c.

Table 4.1 Multi-objective obtained results for IEEE 30-bus Three control variables set system

Control Variable	Load Flow Solution	Minimization of L-index & Cost	Minimization of Cost & Emission	Minimization of L-index & Emission
V_2	1.0338	1.0422	1.0359	1.0442
V_5	0.9814	1.0478	1.0075	1.0415
V_8	1.0230	1.0100	1.0141	1.0240
V_{11}	1.0370	1.0393	1.0425	1.0915
V_{13}	0.9880	1.0507	1.0248	1.0872
t_1	0.9780	1.0750	0.9250	1.0750
t_2	0.9690	1.0500	1.1000	1.0000
t_3	0.9320	1.0000	1.0000	1.1000
t_4	0.9680	1.0250	1.0250	0.9750
Q_{24}	0.0000	5.0000	5.0000	5.0000
Q_{25}	0.0000	4.0000	2.0000	5.0000
Q_{26}	0.0000	5.0000	2.0000	4.0000
Q_{29}	0.0000	3.0000	3.0000	5.0000
Q_{30}	0.0000	4.0000	2.0000	5.0000
L-index	0.092369	0.054598	-	0.049657
COST (\$/hr)	825.37	824.77	824.52	-
EMISSION (ton/hr)	0.45488	-	0.45381	0.45386

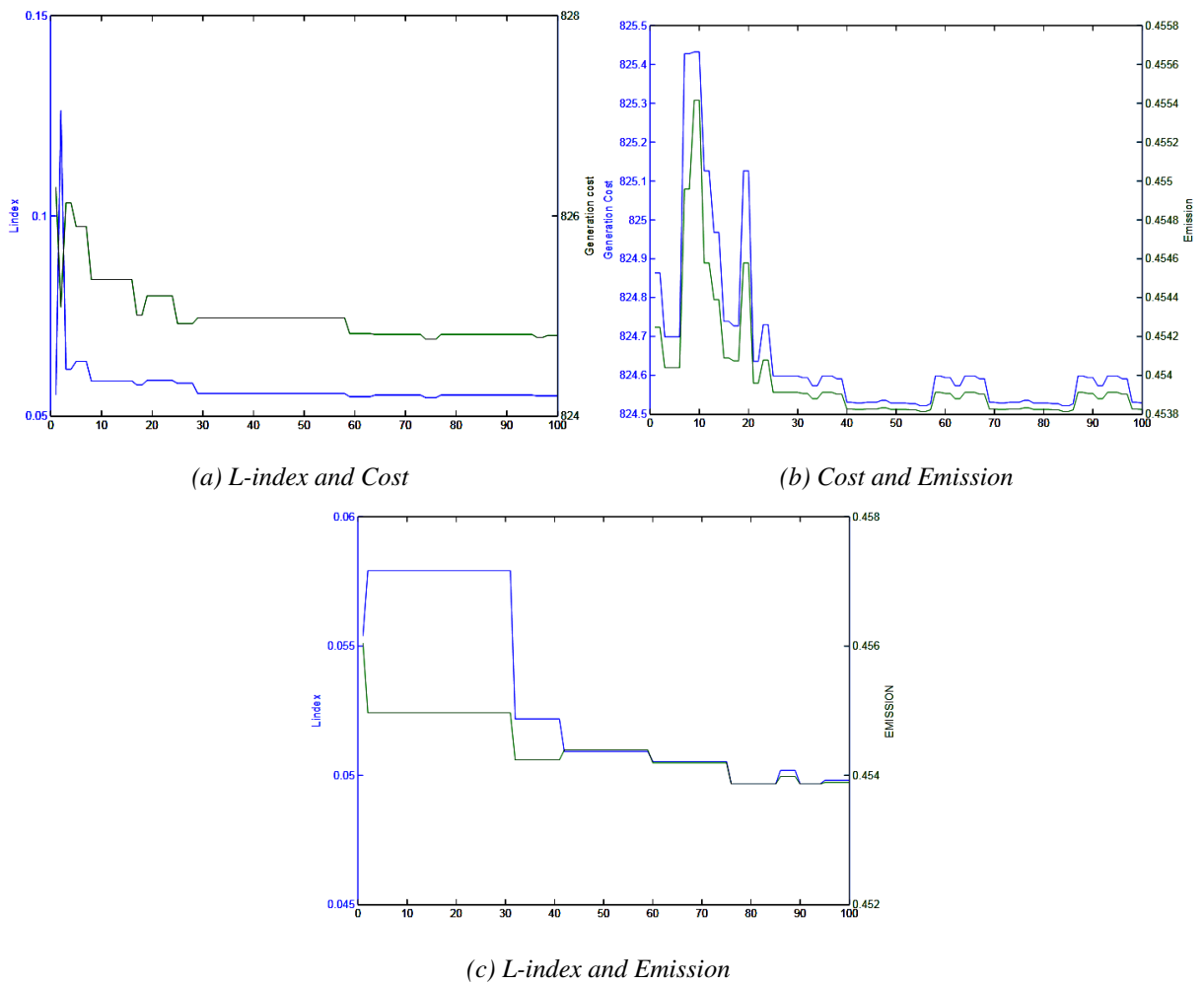


Fig. 4.1 Convergence characteristic of Multi-objective for IEEE 30-bus Three control variables set system

4.4.2 Case-II : Four Control Variables Sets

Four control variables which are used in this case are real power generation (P_g), generator voltages (V_g), the transformer tap changers (t_k) and the switchable VAR sources (Q_c). The proposed Fuzzy-Genetic algorithm is used for solving problem. The result of applying Fuzzy-Genetic algorithm are given in Table 4.2. Fig 4.2 shows the corresponding optimization results.

4.4.2.1 L-index and Generation Cost Minimization

Fig 4.2a shows the optimization results obtained with L-index and generation cost minimization. The best compromise solution of L-index and generation cost minimization are 0.055583 and

808.51 \$/hr respectively, which is 39.8% and 2.07 % reduced from its base case. The result and corresponding setting of the control variables are shown in Table 4.2.

4.4.2.2 Generation Cost and Fuel Emission Minimization

With the simultaneous minimization of generation cost and fuel emission, the best compromise solution are 801.22 \$/hr and 0.40697 ton/hr, which is 2.9 % and 10.5% reduced from its base case. The result and corresponding setting of the control variable are shown in Table 4.2 and Fig 4.2b shows the optimization results obtained with generation cost and emission minimization.

4.4.2.3 L-index and Fuel Emission Minimization

In this case study, developed algorithm has been applied for multi-objectives namely L-index and fuel emission. The optimization results obtained and the corresponding setting of the control variables are given in Table 4.2. The best compromise solutions obtained are 0.053118 and 0.32774 ton/hr, which is 42.4% and 27.9% reduced from its base case. Correspondingly, the optimization results of applying Fuzzy-Genetic algorithm is shown in Fig 4.2c.

Table 4.2 Multi-objective obtained results for IEEE 30-bus Four control variables set system

Control Variable	Load Flow Solution	Minimization of L-index & Cost	Minimization of Cost & Emission	Minimization of L-index & Emission
PG_1	2.3923	2.40000	2.2112	1.8821
PG_2	0.5756	0.63661	0.66810	0.77125
PG_5	0.2456	0.28833	0.43613	0.34583
PG_8	0.3500	0.21269	0.27317	0.32395
PG_{11}	0.1793	0.18227	0.27399	0.27814
PG_{13}	0.1691	0.20284	0.19338	0.31264
V_2	1.0338	1.04890	1.01860	1.03130
V_5	0.9814	1.02550	1.00400	1.02630
V_8	1.0230	1.04760	1.02290	1.04670
V_{11}	1.0374	1.02580	1.04690	1.06550
V_{13}	0.9881	1.03830	1.02950	1.06260
t_1	0.9780	1.07500	1.07500	1.02500

t_2	0.9690	1.10000	0.90000	1.00000
t_3	0.9320	1.00000	1.02500	1.10000
t_4	0.9680	1.07500	0.90000	0.95000
Q_{24}	0.0000	4.0000	4.0000	5.00000
Q_{25}	0.0000	5.0000	5.0000	2.00000
Q_{26}	0.0000	5.0000	3.0000	3.00000
Q_{29}	0.0000	2.0000	2.0000	4.00000
Q_{30}	0.0000	3.0000	1.0000	5.00000
L-index	0.092369	0.055583	-	0.053118
COST (\$/hr)	825.37	808.51	801.22	-
EMISSION (ton/hr)	0.45488	-	0.40697	0.32774

4.5 57-BUS SYSTEM ANALYSIS

The proposed Fuzzy-Genetic algorithm is applied for the improvement of voltage stability is already discussed in the previous cases. The load flow analysis are summarized in Table 4.3, 4.4 and respective value of L-index, generation cost and transmission loss are also given for the base case. From this computation it is found that $L^{max} = 0.13594$ and the five weakest buses are selected (30, 31, 32, 33 and 34) whose L-index values are high. These five buses are selected for reactive power injection. The result of applying Fuzzy-Genetic algorithm are given in Table 4.3, 4.4.

4.5.1 Case-I : Three Control Variables Sets

Three control variables which are used in this case are generator voltages (V_g), the transformer tap changers(t_k) and the switchable VAR sources(Q_c). The proposed Genetic algorithm with Fuzzy decision making is used for solving the multi-objective problems. The results of applying Fuzzy-Genetic algorithm are given in Table 4.3. Fig 4.3 shows the variation in the values of the objective functions with each iteration.

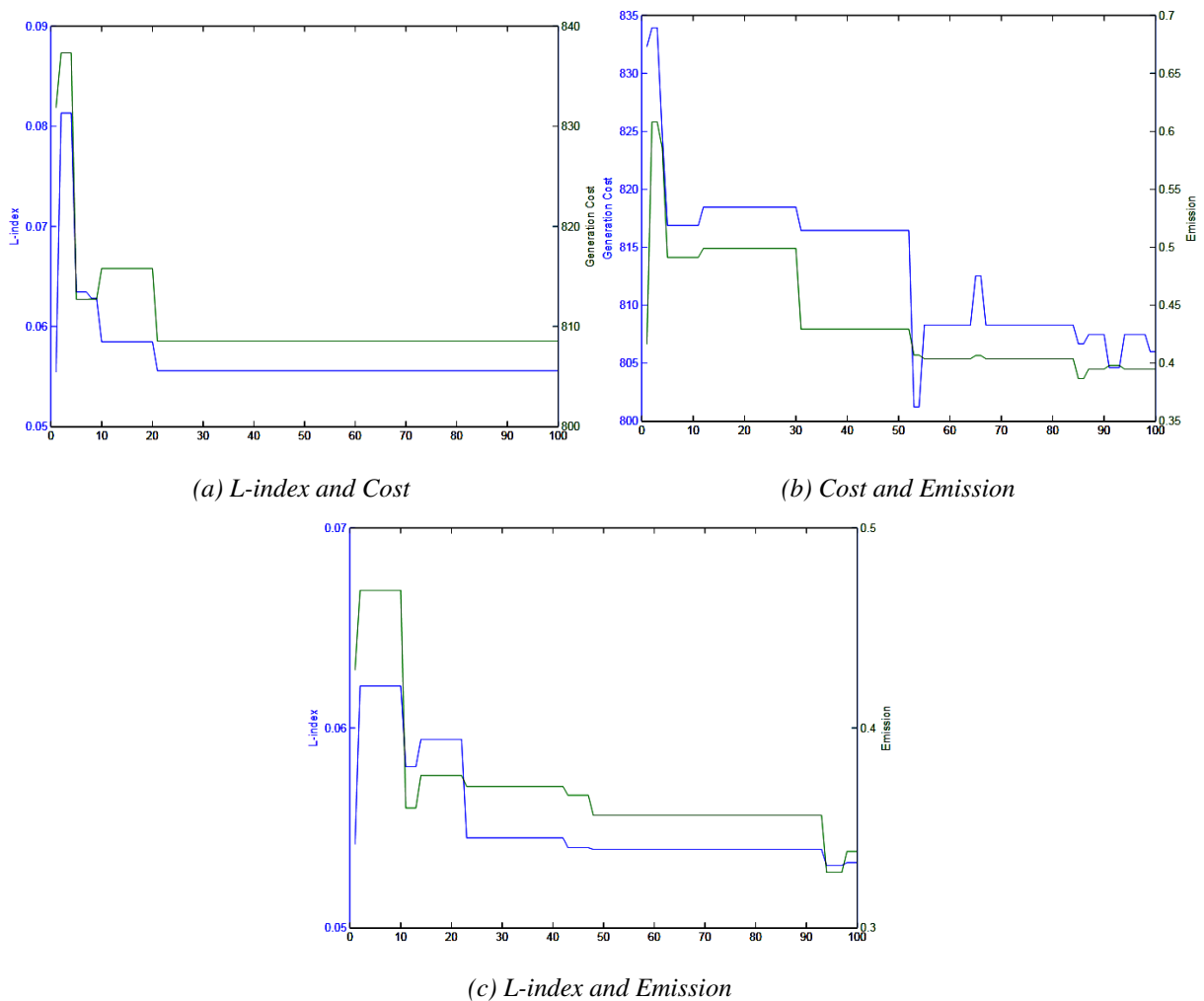


Fig. 4.2 Convergence characteristic of Multi-objective for IEEE 30-bus Four control variables set system

4.5.1.1 L-index and Transmission Loss Minimization

Fig 4.3a shows the Multi-objective solutions for L-index and transmission loss minimization. The solution obtained after applying the Fuzzy-Genetic algorithm on L-index and loss minimization are 0.11606 and 23.517 MW, which is 14.62% and 18.1 % less from its base case. The result and corresponding setting control variables are shown in Table 4.3.

4.5.1.2 Transmission Loss and Generation Cost Minimization

In this case study, developed algorithm is applied for multi-objectives namely transmission loss and generation cost. The optimization results obtained are 23.938 MW and 12043 \$/hr, which is 16.7% and 0.774% reduction respectively from its base case. The result and corresponding control setting are shown in Table 4.3 and Fig 4.3b shows the optimization results of this case.

4.5.1.3 L-index and Generation Cost Minimization

The developed algorithm is applied for multi-objectives namely L-index and generation cost. The optimization results obtained are given in Table 4.3. The best compromise solution obtained are 0.1299 and 12048 \$/hr, which is 4.44% and 0.733% reduced from its base case. Correspondingly, the optimization is also shown in Fig 4.3c.

4.5.2 Case-II : Four Control Variables Sets

Four control variables which are used in this case are real power generation(P_g), generator voltages (V_g), the transformer tap changers(t_k) and the switchable VAR sources(Q_c). The proposed Fuzzy-Genetic algorithm is used for solving problem. The results of applying Fuzzy-Genetic algorithm are given in Table 4.4. Fig 4.4 shows the variation in the values of the objective functions with each iteration.

Table 4.3 Multi-objective obtained results for IEEE 57-bus Three control variables set system

Control Variable	Load Flow Solution	Minimization of L-index & Loss	Minimization of Loss & Cost	Minimization of Cost & L-index
V_2	1.010	1.0142	1.0178	1.0102
V_3	0.985	1.0373	1.0209	1.0102
V_6	0.980	1.0212	1.0160	1.0243
V_8	1.005	1.0236	1.0122	1.0089
V_9	0.980	1.0298	1.0308	1.0278
V_{12}	1.015	1.0041	1.0232	1.0328
t_1	0.970	0.9500	0.9600	1.1000
t_2	0.978	1.1000	1.0800	1.1000
t_3	1.043	0.9700	0.9800	0.9000
t_4	1.000	1.1000	1.0100	0.9200
t_5	1.000	1.0800	0.9900	1.1000
t_6	1.043	1.0100	1.0400	0.9300
t_7	0.967	1.1000	1.0900	1.1000
t_8	0.975	1.1000	0.9400	1.0700
t_9	0.955	1.0700	1.1000	1.1000
t_{10}	0.955	1.0200	1.0600	1.0900
t_{11}	0.900	1.1000	1.0300	1.1000
t_{12}	0.930	1.1000	1.0900	1.1000

t_{13}	0.895	1.0500	1.0000	1.1000
t_{14}	0.958	1.0300	1.0300	1.0200
t_{15}	0.980	1.0800	1.0500	1.0800
t_{16}	0.940	0.9100	0.9800	0.9000
t_{17}	0.958	1.1000	1.0800	1.0800
Q_{30}	0.000	1.0000	2.0000	1.0000
Q_{31}	0.000	1.0000	1.0000	1.0000
Q_{32}	0.000	1.0000	2.0000	1.0000
Q_{33}	0.000	1.0000	5.0000	1.0000
Q_{34}	0.000	1.0000	1.0000	1.0000
L-index	0.13594	0.11606	-	0.1299
Loss (MW)	28.738	23.517	23.938	-
COST (\$/hr)	12137	-	12043	12048

4.5.2.1 L-index and Transmission Loss Minimization

Fig 4.4a shows the Multi-objective solutions for L-index and transmission loss minimization. The best compromise solutions obtained are 0.12967 and 25.586 MW, which is 4.61% and 10.9% reduced from its base case. The result and corresponding setting of the control variables are shown in Table 4.4.

4.5.2.2 Transmission Loss and Generation Cost Minimization

In this case study, developed algorithm is applied for multi-objectives namely transmission loss and generation cost. The optimization results obtained are given in Table 4.4. The best compromise solutions obtained are 27.273 MW and 9115.6 \$/hr, which is 5.09% and 24.8% reduced from its base case. Correspondingly, the optimization result is shown in Fig 4.4b

Table 4.4 Multi-objective obtained results for IEEE 57-bus Four control variables set system

Control Variable	Load Flow Solution	Minimization of L-index & Loss	Minimization of Loss & Cost
PG_1	2.322	0.72723	1.28160
PG_2	0.030	0.71157	0.39883
PG_3	0.410	0.20296	0.46692
PG_6	0.750	0.69495	0.07522

PG_8	1.500	0.50440	0.81701
PG_9	1.210	0.42356	0.11201
PG_{12}	3.770	0.78240	1.12680
V_2	1.010	1.02540	1.00840
V_3	0.985	1.02290	1.04090
V_6	0.980	1.01720	1.01920
V_8	1.005	0.99335	0.97377
V_9	0.980	1.01250	0.99070
V_{12}	1.015	1.02930	0.98909
t_1	0.970	1.02000	0.9400
t_2	0.978	1.10000	0.9400
t_3	1.043	0.99000	0.9600
t_4	1.000	1.95000	1.0300
t_5	1.000	1.06000	1.0400
t_6	1.043	1.02000	1.0300
t_7	0.967	1.10000	1.0700
t_8	0.975	1.10000	0.9800
t_9	0.955	0.90000	1.0900
t_{10}	0.955	1.05000	1.0600
t_{11}	0.900	1.07000	1.0300
t_{12}	0.930	1.03000	0.9700
t_{13}	0.895	1.10000	1.0000
t_{14}	0.958	0.98000	0.9800
t_{15}	0.980	0.99000	0.9700
t_{16}	0.940	0.90000	0.9100
t_{17}	0.958	1.08000	1.0000
Q_{30}	0.000	2.00000	1.0000
Q_{31}	0.000	1.00000	3.0000
Q_{32}	0.000	1.00000	5.0000
Q_{33}	0.000	2.00000	2.0000
Q_{34}	0.000	4.00000	4.0000
L-index	0.13594	0.12967	-
Loss (MW)	28.738	25.586	27.273
COST (\$/hr)	12137	-	9115.6

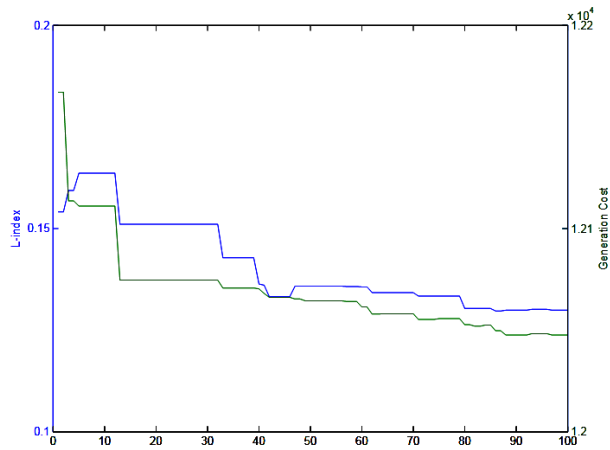
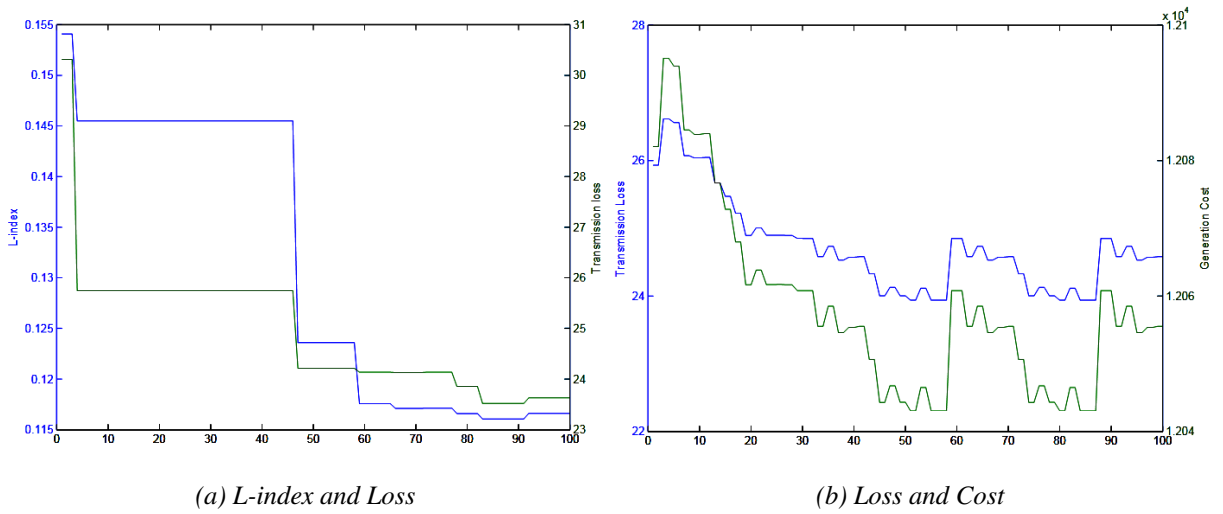


Fig. 4.3 Convergence characteristic of Multi-objective for IEEE 57-bus Three control variables set system

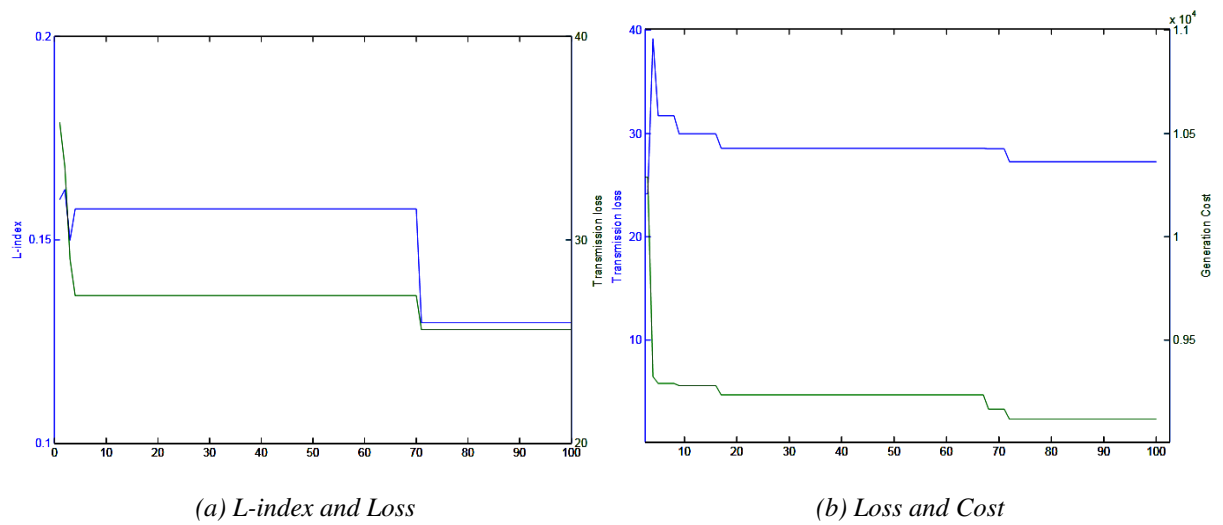


Fig. 4.4 Convergence characteristic of Multi-objective for IEEE 57-bus Four control variables set system

CONCLUSIONS AND FUTURE SCOPE OF WORK

5.1 CONCLUSION

The genetic algorithm (GA) is applied for solving the single-objective OPF problem. With the help of Fuzzy decision making and GA, multi-objective OPF problem is solved. The presented OPF formulation determines the optimum power generation, voltage generation, transformer taps setting and reactive power generation by Capacitor bank. The Generation Cost, Fuel emission, L-index and Transmission are taken as objectives. And also the effect on the objective function by changing the control variable is also observed. The proposed method is applied on 30 and 57 bus test system. The following conclusions are drawn from the study-

- GA is applied for the minimization of objective functions separately, and all are giving better result in comparison to the load flow for both testing system.
- Fuzzy-GA is applied for solving the multi-objective optimization. The algorithm is found effective for different combinations of objectives.
- All the single and multi-objective problems are examined for three and four control variables sets, and the four control variable sets has given more optimal result in comparison to the respective three controls variables sets.

5.2 FUTURE SCOPE OF WORK

- Optimization can be extended to deregulated environment.
- There are various heuristics that are being reported in literature namely teachers-learning based optimization, fire-fly algorithm, civilized swarm optimization. The single and multi-objective formulations mentioned in work can be attempted by these methods.

IEEE 30-Bus System Data

The line, bus data of IEEE 30-bus test system are given in Table A.1, A.2 respectively and diagram is shown in Fig A.1 .

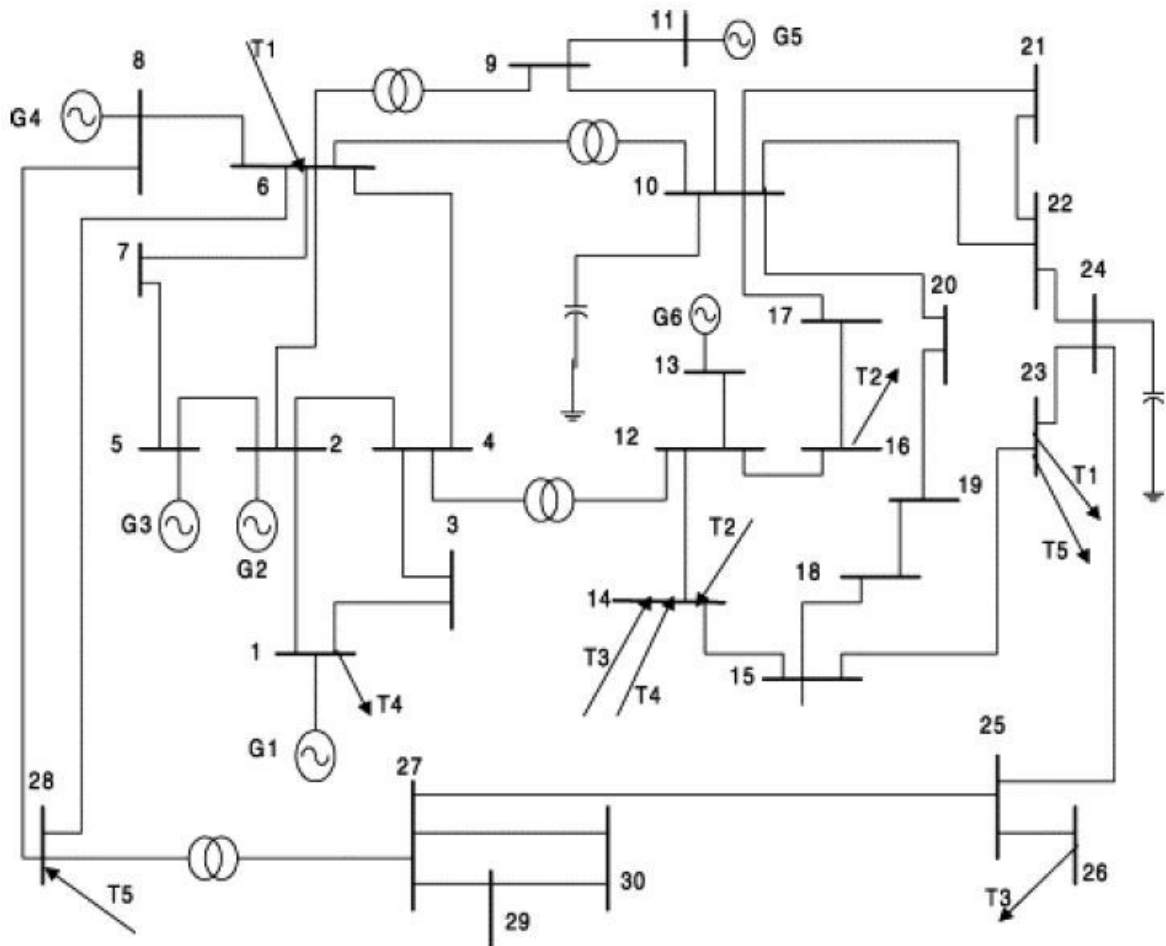


Fig. A.1 IEEE 30-bus system.

Table A.1 Line data of IEEE 30-bus system

From bus	To bus	R (pu)	X (pu)	B/2 (pu)	Tap ratio a
1	2	0.0192	0.0575	0.0528	1.0000
1	3	0.0452	0.1852	0.0408	1.0000
2	4	0.0570	0.1737	0.0368	1.0000
3	4	0.0132	0.0379	0.0084	1.0000
2	5	0.0472	0.1983	0.0418	1.0000
2	6	0.0581	0.1763	0.0374	1.0000
4	6	0.0119	0.0414	0.0090	1.0000
5	7	0.0460	0.1160	0.0204	1.0000
6	7	0.0267	0.0820	0.0170	1.0000
6	8	0.0120	0.0420	0.0090	1.0000
6	9	0	0.2080	0	1.0000
6	10	0	0.5560	0	1.0000
9	11	0	0.2080	0	1.0000
9	10	0	0.1100	0	1.0000
4	12	0	0.2560	0	1.0000
12	13	0	0.1400	0	1.0000
12	14	0.1231	0.2559	0	1.0000
12	15	0.0662	0.1304	0	1.0000
12	16	0.0945	0.1987	0	1.0000
14	15	0.2210	0.1997	0	1.0000
16	17	0.0824	0.1932	0	1.0000
15	18	0.1070	0.2185	0	1.0000
18	19	0.0639	0.1292	0	1.0000
19	20	0.0340	0.0680	0	1.0000
10	20	0.0936	0.2090	0	1.0000
10	17	0.0324	0.0845	0	1.0000
10	21	0.0348	0.0749	0	1.0000
10	22	0.0727	0.1499	0	1.0000
21	22	0.0116	0.0236	0	1.0000

15	23	0.1000	0.2020	0	1.0000
22	24	0.1150	0.1790	0	1.0000
23	24	0.1320	0.2700	0	1.0000
24	25	0.1885	0.3292	0	1.0000
25	26	0.2544	0.3800	0	1.0000
25	27	0.1093	0.2087	0	1.0000
27	28	0	0.3960	0	1.0000
27	29	0.2198	0.4153	0	1.0000
27	30	0.3202	0.6027	0	1.0000
29	30	0.2399	0.4533	0	1.0000
8	28	0.0636	0.2000	0.0418	1.0000
6	28	0.0169	0.0599	0.0130	1.0000

Table A.2 Bus data of IEEE 30-bus system

Bus No.	Bus code	Voltage Mag.	Angle Deg	Load MW	Load MVAR	Gen MW	Gen MVAR	Gen Qmin.	Gen Qmax.
1	1	1.05	0	0	0	0	0	-500	500
2	2	1.0338	0	21.7	12.7	57.56	2.47	-500	500
3	3	1.0	0	2.4	1.2	0	0	-500	500
4	3	1.00	0	7.6	1.6	0	0	-500	500
5	2	1.0058	0	94.2	19	24.56	22.57	-500	500
6	3	1.0	0	0.0	0.0	0	0	-500	500
7	3	1.0	0	62.8	10.9	0	0	-500	500
8	2	1.023	0	80	30	35	34.84	-500	500
9	3	1.0	0	0.0	0.0	0	0	-500	500
10	3	1.0	0	5.8	2.0	0	0	-500	500
11	2	1.0913	0	17.93	30.78	0	0	-500	500
12	3	1.0	0	11.2	7.5	0	0	-500	500
13	2	1.0883	0	0.0	0.0	16.91	37.83	-500	500
14	3	1.0	0	6.2	1.6	0	0	-500	500

15	3	1.0	0	8.2	2.5	0	0	-500	500
16	3	1.0	0	3.5	1.8	0	0	-500	500
17	3	1.0	0	9.0	5.8	0	0	-500	500
18	3	1.0	0	3.2	0.9	0	0	-500	500
19	3	1.0	0	9.5	3.4	0	0	-500	500
20	3	1.0	0	2.2	0.7	0	0	-500	500
21	3	1.0	0	17.5	11.2	0	0	-500	500
22	3	1.0	0	0.0	0.0	0	0	-500	500
23	3	1.0	0	3.2	1.6	0	0	-500	500
24	3	1.0	0	8.7	6.7	0	0	-500	500
25	3	1.0	0	0.0	0.0	0	0	-500	500
26	3	1.0	0	3.5	2.3	0	0	-500	500
27	3	1.0	0	0.0	0.0	0	0	-500	500
28	3	1.0	0	0.0	0.0	0	0	-500	500
29	3	1.0	0	2.4	0.9	0	0	-500	500
30	3	1.0	0	10.6	1.9	0	0	-500	500

The Generation cost coefficient for cost calculation and Emission coefficient for emission calculation are given in Table A.3

Table A.3 Generation cost and emission coefficient of IEEE 30-bus system

Bus No.	P_{min}	P_{max}	a_i	b_i	c_i	γ_i	β_i	α_i	ζ_i	λ_i
1	50	200	0.00375	2.00	0	0.0649	-0.05554	0.04091	0.0002	2.857
2	20	80	0.01750	1.75	0	0.05638	-0.06047	0.02543	0.0005	3.333
5	15	50	0.06250	1.00	0	0.04586	-0.05094	0.04258	0.000001	8
8	10	35	0.0083	3.25	0	0.0338	-0.0355	0.05326	0.002	2
11	10	30	0.025	3.00	0	0.04586	-0.05094	0.04258	0.000001	8
13	10	40	0.025	3.00	0	0.05151	-0.05555	0.06131	0.00001	6.667

IEEE 57-Bus System Data

The line, bus data are given in Table 4.1, 4.2 respectively and diagram is shown in Fig B.1.

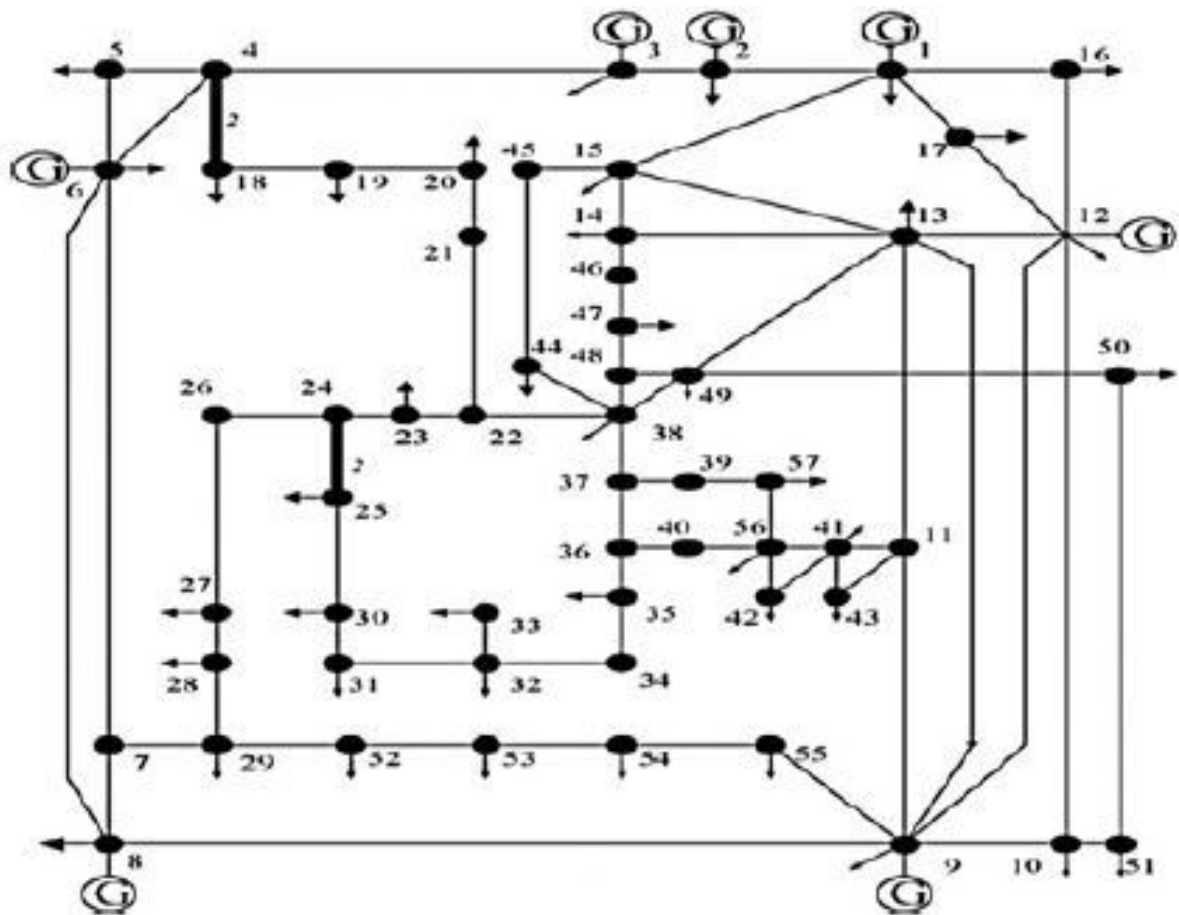


Fig. B.1 IEEE 57-bus system.

Table B.1 Line data of IEEE 57-bus system

From Bus	To Bus	R(pu)	X(pu)	B/2(pu)	Tap ratio a
1	2	0.0083	0.0280	0.0645	1
2	3	0.0298	0.0850	0.0409	1
3	4	0.0112	0.0366	0.0190	1
4	5	0.0625	0.1320	0.0129	1
4	6	0.0430	0.1480	0.0174	1
6	7	0.0200	0.1020	0.0138	1
6	8	0.0339	0.1730	0.0235	1
8	9	0.0099	0.0505	0.0274	1
9	10	0.0369	0.1679	0.0220	1
9	11	0.0258	0.0848	0.0109	1
9	12	0.0648	0.2950	0.0386	1
9	13	0.0481	0.1580	0.0203	1
13	14	0.0132	0.0434	0.0055	1
13	15	0.0269	0.0869	0.0115	1
1	15	0.0178	0.0910	0.0494	1
1	16	0.0454	0.2060	0.0273	1
1	17	0.0238	0.1080	0.0143	1
3	15	0.0162	0.0530	0.0272	1
4	18	0.0	0.5550	0.0	0.970
4	18	0.0	0.4300	0.0	0.978
5	6	0.0302	0.0641	0.0062	1
7	8	0.0139	0.0712	0.0097	1
10	12	0.0277	0.1262	0.0164	1
11	13	0.0223	0.0732	0.0094	1
12	13	0.0178	0.0580	0.0302	1
12	16	0.0180	0.0813	0.0108	1
12	17	0.0397	0.1790	0.0238	1
14	15	0.0171	0.0547	0.0074	1
18	19	0.4610	0.6850	0.0	1

19	20	0.2830	0.4340	0.0	1
21	20	0.0	0.7767	0.0	1.043
21	22	0.0736	0.1170	0.0	1
22	23	0.0099	0.0152	0.0	1
23	24	0.1660	0.2560	0.0042	1
24	25	0.0	1.1820	0.0	1
24	25	0.0	1.2300	0.0	1
24	26	0.0	0.0473	0.0	1.043
26	27	0.1650	0.2540	0.0	1
27	28	0.0618	0.0954	0.0	1
28	29	0.0418	0.0587	0.0	1
7	29	0.0	0.0648	0.0	0.967
25	30	0.1350	0.2020	0.0	1
30	31	0.3260	0.4970	0.0	1
31	32	0.5070	0.7550	0.0	1
32	33	0.0392	0.0360	0.0	1
34	32	0.0	0.9530	0.0	0.975
34	35	0.0520	0.0780	0.0016	1
35	36	0.0430	0.0537	0.0008	1
36	37	0.0290	0.0366	0.0	1
37	38	0.0651	0.1009	0.0010	1
37	39	0.0239	0.0379	0.0	1
36	40	0.0300	0.0466	0.0	1
22	38	0.0192	0.0295	0.0	1
11	41	0.0	0.7490	0.0	0.955
41	42	0.2070	0.3520	0.0	1
41	43	0.0	0.4120	0.0	1
38	44	0.0289	0.0585	0.0010	1
15	45	0.0	0.1042	0.0	0.955
14	46	0.0	0.0735	0.0	0.900

46	47	0.0230	0.0680	0.0016	1
47	48	0.0182	0.0233	0.0	1
48	49	0.0834	0.1290	0.0024	1
49	50	0.0801	0.1280	0.0	1
50	51	0.1386	0.2200	0.0	1
10	51	0.0	0.0712	0.0	0.930
13	49	0.0	0.1910	0.0	0.895
29	52	0.1442	0.1870	0.0	1
52	53	0.0762	0.0984	0.0	1
53	54	0.1878	0.2320	0.0	1
54	55	0.1732	0.2265	0.0	1
11	43	0.0	0.1530	0.0	0.958
44	45	0.0624	0.1242	0.0020	1
40	56	0.0	1.1950	0.0	0.958
56	41	0.5530	0.5490	0.0	1
56	42	0.2125	0.3540	0.0	1
39	57	0.0	1.3550	0.0	0.980
57	56	0.1740	0.2600	0.0	1
38	49	0.1150	0.1770	0.0015	1
38	48	0.0312	0.0482	0.0	1
9	55	0.0	0.1205	0.0	0.940

Table B.2 Bus data of IEEE 57-bus system

Bus No.	Bus code	Voltage Mag.	Angle Deg	Gen MW	Gen MVAR	Load MW	Load MVAR	Gen Qmin.	Gen Qmax.
1	1	1.040	0	0.0	0.0	0.0	0.0	-500	500
2	2	1.010	0	3.0	88.0	0.0	0.8	-500	500
3	2	0.985	0	41.0	21.0	40.0	1.0	-500	500
4	3	1.000	0	0.0	0.0	0.0	0.0	-500	500
5	3	1.000	0	13.0	4.0	0.0	0.0	-500	500

6	2	0.980	0	75.0	2.0	0.0	0.8	-500	500
7	3	1.000	0	0.0	0.0	0.0	0.0	-500	500
8	2	1.005	0	150.0	22.0	450.0	62.1	-500	500
9	2	0.980	0	121.0	26.0	0.0	2.2	-500	500
10	3	1.000	0	5.0	2.0	0.0	0.0	-500	500
11	3	1.000	0	0.0	0.0	0.0	0.0	-500	500
12	2	1.015	0	377.0	24.0	310.0	128.5	-500	500
13	3	1.000	0	18.0	2.3	0.0	0.0	-500	500
14	3	1.000	0	10.5	5.3	0.0	0.0	-500	500
15	3	1.000	0	22.0	5.0	0.0	0.0	-500	500
16	3	1.000	0	43.0	3.0	0.0	0.0	-500	500
17	3	1.000	0	42.0	8.0	0.0	0.0	-500	500
18	3	1.000	0	27.2	9.8	0.0	0.0	-500	500
19	3	1.000	0	3.3	0.6	0.0	0.0	-500	500
20	3	1.000	0	2.3	1.0	0.0	0.0	-500	500
21	3	1.000	0	0.0	0.0	0.0	0.0	-500	500
22	3	1.000	0	0.0	0.0	0.0	0.0	-500	500
23	3	1.000	0	6.3	2.1	0.0	0.0	-500	500
24	3	1.000	0	0.0	0.0	0.0	0.0	-500	500
25	3	1.000	0	6.3	3.2	0.0	0.0	-500	500
26	3	1.000	0	0.0	0.0	0.0	0.0	-500	500
27	3	1.000	0	9.3	0.5	0.0	0.0	-500	500
28	3	1.000	0	4.6	2.3	0.0	0.0	-500	500
29	3	1.000	0	17.0	2.6	0.0	0.0	-500	500
30	3	1.000	0	3.6	1.8	0.0	0.0	-500	500
31	3	1.000	0	5.8	2.9	0.0	0.0	-500	500
32	3	1.000	0	1.6	0.8	0.0	0.0	-500	500
33	3	1.000	0	3.8	1.9	0.0	0.0	-500	500
34	3	1.000	0	0.0	0.0	0.0	0.0	-500	500
35	3	1.000	0	6.0	3.0	0.0	0.0	-500	500

36	3	1.000	0	0.0	0.0	0.0	0.0	-500	500
37	3	1.000	0	0.0	0.0	0.0	0.0	-500	500
38	3	1.000	0	14.0	7.0	0.0	0.0	-500	500
39	3	1.000	0	0.0	0.0	0.0	0.0	-500	500
40	3	1.000	0	0.0	0.0	0.0	0.0	-500	500
41	3	1.000	0	6.3	3.0	0.0	0.0	-500	500
42	3	1.000	0	7.1	4.4	0.0	0.0	-500	500
43	3	1.000	0	2.0	1.0	0.0	0.0	-500	500
44	3	1.000	0	12.0	1.8	0.0	0.0	-500	500
45	3	1.000	0	0.0	0.0	0.0	0.0	-500	500
46	3	1.000	0	0.0	0.0	0.0	0.0	-500	500
47	3	1.000	0	29.7	11.6	0.0	0.0	-500	500
48	3	1.000	0	0.0	0.0	0.0	0.0	-500	500
49	3	1.000	0	18.0	8.5	0.0	0.0	-500	500
50	3	1.000	0	21.0	10.5	0.0	0.0	-500	500
51	3	1.000	0	18.0	5.3	0.0	0.0	-500	500
52	3	1.000	0	4.9	2.2	0.0	0.0	-500	500
53	3	1.000	0	20.0	10.0	0.0	0.0	-500	500
54	3	1.000	0	4.1	1.4	0.0	0.0	-500	500
55	3	1.000	0	6.8	3.4	0.0	0.0	-500	500
56	3	1.000	0	7.6	2.2	0.0	0.0	-500	500
57	3	1.000	0	6.7	2.0	0.0	0.0	-500	500

The generator data for cost calculation of the IEEE-57 bus system are given in Table B.3.

Table B.3 Generation cost coefficient of IEEE 57-bus system

Bus No.	a_i	b_i	c_i	P_{min}	P_{max}
1	0.0775795	20	0	0	100
2	0.01	40	0	0	140
3	0.025	20	0	0	100
6	0.01	40	0	0	100
8	0.0222222	20	0	0	100
9	0.01	40	0	0	100
12	0.0322581	20	0	0	100

References

- [1] Victoria L. Vickers, Walter J. Hobbbs, S. Vemuri, and Daniel L. Todd. Fuel resource scheduling with emission constraints. *IEEE Trans Power Syst*, 9(3):1531 – 38, Aug 1994.
- [2] C.M. Huang and Y.C. Huang. A novel approach to real-time economic emission power dispatch. *IEEE Trans Power Syst*, 18(18):288 – 94, Feb 2003.
- [3] J.H. Talaq and M.E. El-Hawary. Minimum emission power flow. *IEEE Trans Power Syst*, 9(1):429 – 35, Feb 2003.
- [4] J. Carpentier, R. Girard, and E. Scano. Voltage collapse proximity indicators computed from an optimal power flow. In *Proc. of 8th PSCC Conference, Helsinki*, 1984.
- [5] H. Saadat. *Power System Analysis*. Tata Mc-Grawhill, New Delhi, 2002.
- [6] A.D. Papalexopoulos, C.F. Imparato, and F.F. Wu. Large- scale optimal power flow: Effects of initialization, decoupling & discretization. *IEEE Trans Power Syst*, 4(2):748 – 59, May 1989.
- [7] K. Deb. *Multi-objective Optimization using Evolutionary Algorithm*. John Wiley & Sons,Ltd, 2010.
- [8] H.W. Dommel and W.F. Tinney. Optimal power flow solution. *IEEE Trans Power Syst*, 87:1866 – 76, Oct 1968.
- [9] Y.L. Hu and W.G. Wee. A hierarchical system for economic dispatch with environmental constrains. *IEEE Trans Power Syst*, 9(2):1076 – 82, May 1994.
- [10] R. Ramanathan. Emission constrained economic dispatch. *IEEE Trans Power Syst*, 9(4):1994 – 2000, Nov 1994.
- [11] S.D. Chen and J.F. Chen. A direct newton-raphson economic emission dispatch. *International Journal of Electrical Power and Energy Systems*, 25:411 – 417, June 2003.

-
- [12] G.F. Reid and L. Hasdorff. Economic dispatch using quadratic programming. *IEEE Trans. on Power Apparatus & Systems*, PAS-92:2015 – 2023, Nov 1973.
- [13] A. Tiranuchit and R.J. Thomas. A posturing strategy against voltage instability in electric power systems. *IEEE Trans Power Syst*, 3:87 – 93, 1988.
- [14] A. Bansilal, D. Thukaram, and K. Parthasarathy. Optimal reactive power dispatch algorithm for voltage stability improvement. *Int J Electr Power Energy Syst*, 18:461 –468, 1996.
- [15] P. Kessel and H. Glavitsch. Estimating the voltage stability of a power system. *IEEE Transactions on Power Delivery*, 3(3):346 – 354, July 1986.
- [16] D. Thukaram, K. Parthasarathy, H.P. Khincha, and A. Bansilal. Voltage stability improvement: case studies of indian power networks. *Electric Power and Systems Research*, 44:35 – 44, Aug 1998.
- [17] M. Nanba, Y. Huang, T. Kai, and S.I. Wamoto. Studies on vipi based control methods for improving voltage stability. *Int J Electr Power Energy Syst*, 20(2):141 – 6, 1998.
- [18] R.S. Tare and P.R. Bijwe. A new index for voltage stability monitoring and enhancement. *Int J Electr Power Energy Syst*, 20(5):345 – 51, 1998.
- [19] R. Raghunatha, R. Ramanujam, K. Parthasarathy, and D. Thukaram. Optimal static voltage stability improvement using a numerically stable slp algorithm for real time applications. *Int J Electr Power Energy Syst*, 21:289 – 97, oct 1999.
- [20] S.C. Choube, L.D. Arya, and D.P. Kothari. Voltage security enhancement using static voltage stability index. In *11th National power systems conference, Bangalore*, pages 154 – 159, 2000.
- [21] D. Devaraj and R.J. Preetha. Genetic algorithm based reactive power dispatch for voltage stability improvement. *Int J Electr Power Energy Syst*, 32:1151 – 1156, June 2010.
- [22] N. Srinivas and K. Deb. Multi-objective function optimization using non-dominated sorting genetic algorithms. *IEEE Transactions on Evolutionary Computation*, 2:221 – 248, 1995.
- [23] O. Alsac and B. Stott. Optimal load flow with steady state security. *IEEE Trans Power Syst*, 94:745 – 51, 1974.

-
- [24] V. Miranda, D. Srinivassan, and L.M. Proenca. Evolutionary computation in power systems. *Int J Electr Power Energy Syst*, 20(2):89 – 98, 1998.
- [25] I. Kenji. Reactive power optimization by genetic algorithm. *IEEE Trans Power Syst*, 9(2): 658 – 92, May 1994.
- [26] M. Younes, M. Rahli, and K.L. Abdelhakem. Optimal power flow based on hybrid genetic algorithm. *Information Science And Engineering*, 23:1801 – 16, 2007.
- [27] M. Varadarajan and K.S. Swarup. Differential evolutionary algorithm for optimal reactive power dispatch. *Int J Electr Power Energy Syst*, 30(8):435 – 41, 2008.
- [28] T. Numnonda and U.D. Annakkage. Optimal power dispatch in multinode electric market using genetic algorithm. *Electric Power Systems Research*, 49:211 – 20, 1999.
- [29] G.A. Taylor, Y.H. Song, and R. He. Multiobjective optimal reactive power flow including voltage security and demand profile classification. *Int J Electr Power Energy SystPower Energy Syst*, 30:327 – 336, 2008.
- [30] T. Niknam, M.R. Narimani, J. Aghaei, and A.R. Azizipanah. Improved particle swarm optimisation for multi-objective optimal power flow considering the cost, loss, emission and voltage stability index. *IET Generation, Transmission & Distribution*, 6(6):515 – 27, Sept 2011.