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Optimization of Voltage Stability Improvement with L-index using Gentic Algorithm

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Abstract — ***The voltage stability analysis and the improvement methodologies are important because increase in demand of electricity is causing voltage drop and thermal stress which may lead to voltage collapse. A Genetic algorithm (GA) is used to solve the optimal power flow (OPF) problem for voltage stability improvement. The voltage stability is measured through L-index to find the vulnerable buses for the placement of compensating devices. The control variables are identified to minimize the maximum value of L-indices. The effect of changing the number of control variables is also studied and the algorithm is tested on IEEE 30-bus and 57-bus systems.***

Keywords- bus test system, Genetic algorithm, Optimization, Power flow, Voltage collapse, Voltage stability index.

I. INTRODUCTION

In present era, the voltage stability is the main challenge to power system planners due to increase in demand. There is a discrepancy between generation and distribution capacity expansion which thereby leading to system operation in hassled condition. The system is hassled mainly due to higher load which leads to some of the system parameters attaining the values close to their limits or even violating the limits. In the condition of voltage collapse due to contingencies such as line outages, inability of power system occurs to meet reactive power requirement.

The phenomenon of voltage instability has been done by researches and the following suggestion and remedies are provided for protecting the power system network failures.

As per researcher methodology and previous work done, two types of approaches carried out for solving voltage instability - preventing control and corrective control. The preventing control involves preventing action for keeping away the operating point from the point of collapse. The corrective control works after the contingency has occurred i.e. voltage stability is endangered. The main objective of the work is to maintain voltage stability, which is used to operate in short-term operation planning framework. In the improvement of voltage stability the existing facilities and equipment operational limits are considered.

Reactive power and voltage control is necessary for maintaining the voltage stability in the power system. The purpose of reactive power and voltage control in the power system is to identify the control variables which minimize the objective function. Proper setting of the control variables such as real power generation, generator voltage, transformer tap changers, switchable VAR sources are necessary for minimization of the objective function.

Many successful methods have been available in the literature to solve the OPF problem. Generalized reduced gradient, linear programming, Newton method, quadratic programming, P-Q decomposition are some methods applied for solving the OPF problem previously. All the above mathematical techniques have some drawbacks such as being trapped in local optima or they are suitable for considering a specific objective function in the OPF problem [1]. Bansilal et al. [2] have been proposed a non-linear least squares optimization algorithm for voltage stability assessment. The indicator (L-index) was presented by Carpentier [3], which is used for computation of optimal power flow. The practice of the indicator L-index as voltage stability assessment for online testing of power system is based on load flow [4]. In ref [5] two control methods for improving voltage stability based on concept of Voltage Instability Proximity Index (VIPI) have been described. In the first control method Successive Quadratic Programming method was used to maximize the value of VIPI for optimal controls calculation under various system conditions. In second control method using the sensitivity of VIPI, for determining the controls needed to maintain the specified threshold value. Tare and Bijwe [6] have reported a index that based on the angle between real and reactive power gradient vectors of load buses. Simple and efficient computational algorithm is used to solve the indices and the indices have been 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 of the voltage stability constrained was enhanced. In ref [7] sequential primal dual LP algorithm was proposed for improving the static voltage stability margin. The proposed algorithm have been improved the system static voltage stability by minimizing the voltage stability index. In ref [8] linearized incremental model has been used for the minimization of reactive power injection, which is necessary for maintaining the level of voltage security (voltage stability indices), if voltage stability index is enhanced than load bus voltage increases significantly. Now, in ref [9] an introduction of Evolutionary computation techniques (Genetic algorithm, Evolutionary programming Genetic programming and classified systems) and their usage in there related fields are given. In ref Varadarajan and Swarup [10] differentially evolutionary optimization algorithm has been presented for solving the reactive power dispatch problem. In [11] Genetic algorithm approach for voltage stability enhancement in the real power loss and voltage stability index was considered. Sharma and Singh [10] provide a summary of Enhanced genetic algorithms (EGA) to solve the optimal power flow (OPF) problem where unit active power outputs and generator-bus voltages magnitude was considered as continuous control variables, transformer tap settings and switchable shunt devices as discrete control variables. Genetic algorithm is used here for solving non-linear voltage stability enhancement problem. The GA is used for locating the optimal value of the decision variable in order to optimize the problem. Two control variable sets are deliberated here, and the effect is examined on non-linear voltage stability problem using Genetic algorithm. Mostly, binary string is used for the representation of the control variables of optimization problem in Genetic algorithm population. The conventional binary-coded GA has hamming cliff problems so; sometime it is difficult to code continuous variables. To overcome the problem real coded Genetic algorithm is used instead of binary coded decision variables. Real coded Genetic Algorithm possesses a lot of advantages than its binary coded counterpart when dealing with continuous search spaces with large dimensions and a great numerical precision is required. In real coded GA, each gene represents a variable of the problem, and the size of the chromosome is kept the same as the length of the solution to the problem. The effect on the objective functions by considering different number of control variable is examined by using GA. IEEE 30-bus and 57-bus test system is presented to illustrate the efficiency of the proposed method.

II. MATHEMATICAL PROBLEM FORMULATION

The purpose of the OPF is to determine the control variables for minimizing the objective function along with satisfied the equality and inequality constraints. The OPF problem can be formulated in the following form:

$$\text{Min } F(x) \quad (1)$$

$$\text{s/t } g(x) = 0 \quad (2)$$

$$h(x) \geq 0 \quad (3)$$

Where, F is the objective function, g is the equality constraints, h is the inequality constraints and x is the control variable. The objectives function, equality and inequality constraints are described as follows.

2.1. Minimization of the voltage stability index (L-index)

In the voltage stability analysis two factors are involved i.e. static and dynamic factor. In the dynamic factor computation takes lots of time, therefore static factor is mostly preferred for voltage stability assessment and control. In the static analysis, index is determined i.e. voltage stability index.

This index measured the closeness of the system to voltage collapse. Various methods are available in the literature for the calculation of the voltage stability index. L-index is one of the methods that are proposed in [11] which is based on load flow analysis. In this method the value of L-index varies from 0 to 1, where 1 represents the voltage collapse and 0 is no load condition. Higher value of L-index represents the most vulnerable bus in the system. Therefore, static voltage stability can be maintained by minimizing the L_{max} index. It is mathematically stated as:

$$F(x) = \text{Minimize } (L^{max}) \quad (4)$$

L-index for jth node is given by:

$$L_j = \left| 1 - \sum_{i=1}^{N_g} F_{ji} \frac{V_i}{V_j} \angle(\theta_{ij} + \delta_i - \delta_j) \right| \quad (5)$$

$$F_{LG} = -[Y_{LL}]^{-1}[Y_{LG}] \quad (6)$$

$$\begin{bmatrix} I_G \\ I_L \end{bmatrix} = \begin{bmatrix} Y_{GG} & Y_{GL} \\ Y_{LG} & Y_{LL} \end{bmatrix} \begin{bmatrix} V_G \\ V_L \end{bmatrix} \quad (7)$$

For N-bus system, Ng comprises the generator bus in which the relationship between voltage and current is having explained by the equation (7), V_G; V_L and I_G; I_L are the voltage and current of the generator and load buses, F(x) is the voltage stability index i.e L-index, Vi, Vj are the voltage magnitude of the ith and jth generator buses, θij is the phase angle of the Fji, δi; δj are the voltage phase angle of i_{th} and j_{th} generator units.

2.2. Equality Constraints:

The real and reactive power balance is used as equality constraints:

$$P_i - V_i \sum_{j=1}^{N} V_j \left[G_{ij} \cos\delta_{ij} + B_{ij} \sin\delta_{ij} \right] = 0; \quad (8)$$

$$Q_i - V_i \sum_{j=1}^{N} V_j \left[G_{ij} \sin\delta_{ij} - B_{ij} \cos\delta_{ij}\right] = 0; \qquad (9)$$

2.3. Inequality Constraints:
The inequality constraints are incorporated to ensure system security, because it reflects the limits on the physical devices of the power system. Inequality constraints are expressed in the following equations:

Real power generation limits:
$P_{gi}^{min} \le P_{gi} \le P_{gi}^{max}$; $i = 1,2,\ldots\ldots,N$ (10)

Reactive power generation limits:
$Q_{gi}^{min} \le Q_{gi} \le Q_{gi}^{max}$; $i = 2,3,\ldots\ldots,N$ (11)

Generation bus voltage limits:
$V_i^{min} \le V_i \le V_i^{max}$; $i = 1,2,\ldots\ldots,N$ (12)

Capacitor bank reactive power generation limits:
$Qc_i^{min} \le Q_{ci} \le Q_{ci}^{max}$; $i = 1,2,\ldots\ldots,N$ (13)
N_{cap} are the numbers of capacitor banks

Transformers tap setting limits:
$t_k^{min} \le t_k \le t_k^{max}$; $i = 1,2,\ldots\ldots,N$ (14)
N_{tran}, the numbers of transformer setting branches.

Line flow limit:
$S_i \le S_i^{max}$; (15)

2.4. Aggregated Objective Function:
The quadratic penalty factor is added to the objective function to handle the inequality constraints. The control vector which violates the constraints will be penalized by these penalty factors which will be deleted automatically in subsequent iterations. With the penalty functions, the new objective function becomes:

$$\min f = F(X) + SL + \sum_{j=1}^{N_{PQ}} VP_j + \sum_{j=1}^{N_g} QP_j + \sum_{j=1}^{N_l} LF_j \qquad (16)$$

Where, SL is the reference bus generator active power limit violation. VPj is the load bus voltage limit violation. QPj is the reactive power generation limit violation. LFj is the line flow limit violation. These factors are defined as:

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

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

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

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

Where, K_{sl}, K_v, K_q and K_{lf} are the penalty factors. Effectiveness of the penalty function is depending on selection of the value of the penalty factor.

III. METHOD ADOPTED

In evolutionary algorithm (EA), the main key element is evolutionary process to approach well designed and optimum system which imply the best results carried out for implementation. More techniques are involved to find optimum solution in which Genetic Algorithm (GA) is very popular. EA is based on natural selection and natural genetics. GA is population based optimization approach. Some improvement has been carried out for improving the capability of GA to solve the optimization problem in Binary coded GA. Primarily the decision variables are represented in the real and integer values instead of binary strings in the chromosomes. Such form of representation of chromosomes has some advantages over binary coding in terms of efficiency. The efficiency of GA is increased to modify optimum solution avoiding local minima problems. Some more advantages such as no need of converting binary to decimal and vice-versa conversion (i.e., no Hamming cliff problem) and less memory space requirement are overcome which made more concerns to researchers to solve OPF. 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 stated below.

3.1. Initialization:

Firstly chromosomes of the population are generated randomly. In the population 30 chromosomes exist and in each chromosome 19 genes are present in case of 30-bus 4 control variable set system. The 19 genes are five generator voltage (PV bus), five generator active power, four transformer tap setting and five switchable VAR sources. After generation of population Y-bus and load flow is solved for each chromosome of the population and from the result of the load flow dependent and independent variables are calculated and then verified the limitation of the constraints. The generator bus voltage varies from 0.95 to 1.05 p.u., transformer tap setting varies from 0.9 to 1.1 p.u. with step size of 0.025 p.u. and switchable VAR sources varies from 1 to 5 with a step size of 1.

$$X = [P_g, V_g, TAP, Q_c]_{1xn} \quad (17)$$
$$P_{gi} = [P_{g2}, P_{g3} \ldots P_{g(N-1)}]_{1x(N-1)} \quad (18)$$
$$V_g = [V_{g2}, V_{g3} \ldots V_{gN}]_{1xN} \quad (19)$$
$$TAP = [TAP_1, TAP_2 \ldots TAP_{Ntran}]_{1x\,Ntran} \quad (20)$$
$$Q_{gi} = [Q_{c1}, Q_{c2} \ldots Q_{cNcap}]_{1x\,Ncap} \quad (21)$$
$$N = (N_{tran} + N_{cap} + N_{gen} + (N_{gen} - 1)) \quad (22)$$

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.

3.2. Selection Operator:

From the values of dependent and independent variables the objective function is calculated. Based on the results of objective function the chromosomes are arranged in ascending order and reproduction (selection) operation is applied. Selection is the process in which individual strings are copied according to the value of objective function. The best solution is passed from selection process and bad/unfitted solutions are eliminated but population size is kept constant. Tournament selection is used here, tournament selection is played between two solutions and the better solution is chosen and placed in the mating pool. Process is continued and filled all the slots of mating pool with the better solution. It is most popular selection method because of its simplicity.

3.3. Crossover Operator:

In crossover operation two parents are selected randomly from the parent pool then crossover operation is applied and new offspring are produced, it is called the global search property of the GA. For new chromosomes production, information is exchanged between two off springs of the mating pool for new offspring. Here real and integer variable are considered instead of the binary so, each chromosome in the population consist of two types of variable; real and integer. Firstly the chromosomes are cut at the boundary between the float and integer variables and chromosomes are separated in two parts. Then separate crossover is applied for real and integer value. Two-point crossovers are applied for integer value 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 for 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 $\alpha|u_i(j) - u_j(k)|$ on either side of the region bounded by the parents. Fig 1 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 e1 and e2 are:

$$e_1 = u_1 - \alpha I \quad (23)$$

$$e_2 = u_2 - \alpha I \quad (24)$$

Where, I = u_1 - u_2, α = 0.5, e_1 and e_2 will lie between u_{min} (lower bound) and u_{max} (upper bound). One of the important features of blend crossover is that it depends on the location of the parents. If both parents are closed to each other than new point is also close/similar to the parents otherwise the search becomes the random search.

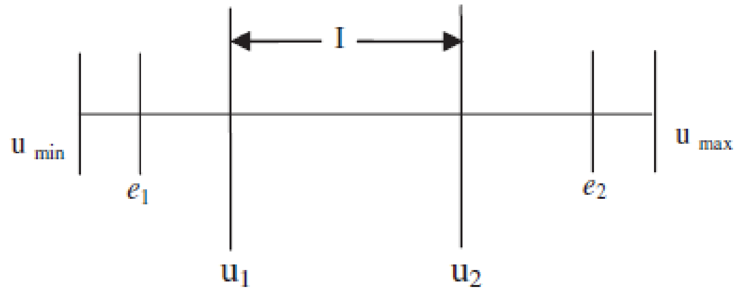

Fig.1. Schematic representation of BLX- α crossover

3.4. 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 plays a dominant role in the evolutionary process. Mutation operation changes the variables randomly with small probability. As in crossover operation, separate crossover is applied for real and integer variable same as in mutation. If the selected number in the mutation process is real then the number is replaced by the uniform number which is in between the lower and upper limit and it is called as the uniform mutation. Otherwise, applying the boundary mutation, this can replace the selected integer variable with its boundary limits.

IV. GENERAL PROCEDURE OF GENETIC ALGORITHM

The general procedure for the implementation of Genetic Algorithm is as follows

Step1: Initialize the population.
Step2: Solve power balance equation using NR method and evaluate the value of fitness function.
Step3: Select two parents randomly from the population for reproduction.
Step4: Apply crossover and mutation.
Step5: Evaluate the fitness function of each chromosome in the population.
Step6: If the end condition is satisfied stop and return the best solution.
Step7: Otherwise go to step 2

V. RESULTS

The applied Genetic algorithm is carried out to solve single objective OPF problem with effective results on IEEE-30 and IEEE-57 bus test system. The results are obtained with reference of two cases as three control variable sets and four control variable sets.

5.1. IEEE 30-BUS SYSTEM

Firstly the genetic algorithm is applied on IEEE-30 bus test system to obtain optimum solution. This test is equipped with six generators, twenty four load buses, and forty one 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 is carried out in Table 1 and 2 for three variables and four variables respectively having base value of L-index. The value of L-index is computed as 0.092369 and the value of L-index is very high for five weakest buses as 24, 25, 26, 29 and 30. From load flow analysis, the buses are selected for reactive power injection.

5.1.1. Case1: Three Control Variable Sets

In this first case three control variable sets are considered as control variables. The control variable sets are generator voltages (Vg) whose lower and upper limits are 0.95 p.u. and 1.1 p.u. respectively, the transformer tap changers(TAP) whose limits is in between 0.9 p.u. to 1.1 p.u. and the switchable VAR sources(Qc) which is always kept within the range of 1 p.u. to 5 p.u. The proposed Genetic algorithm is used for solving optimization problem and results are shown in Table 1. The objective is to minimize the maximum value of L-index, after load flow L-index value is 0.092369 and after applying OPF with GA is 0.050846 that means there is reduction of 44.9% in L-index. The comparison between voltages after the load flow and GA is shown in Fig 2.

Table 1 Control Variables Optimized Using Genetic Algorithm for 30-Bus System with Three Variables Sets

Control Variables	Load Flow Solution	L-index Minimized
V_2	1.0338	1.0636
V_5	0.98196	1.0059
V_8	1.023	1.0243
V_{11}	1.037	1.0097
V_{13}	0.988	1.0462
t_1	0.978	1.075
t_2	0.969	1.1
t_3	0.932	1.1
t_4	0.968	1
Q_{24}	0	5
Q_{25}	0	5
Q_{26}	0	5
Q_{29}	0	5
Q_{30}	0	5
L-index	**0.092369**	**0.050846**

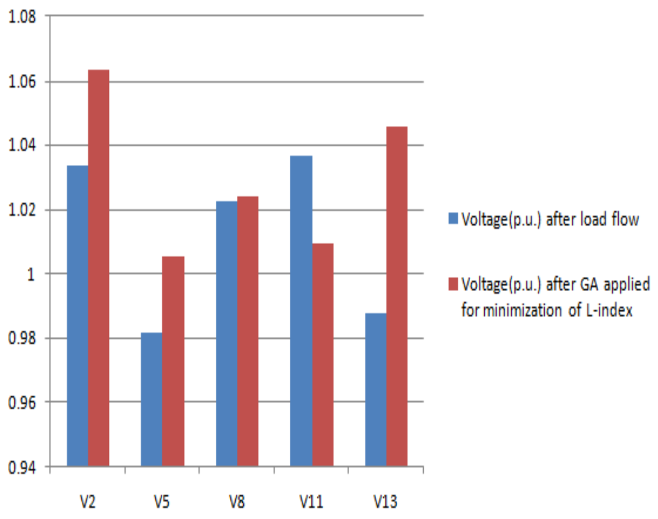

Fig. 2. Voltage profile of 30 Bus three variable

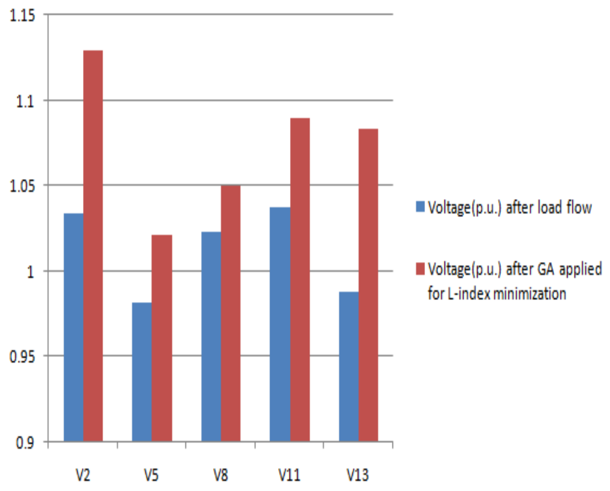

Fig. 3. Voltage profile of 30 Bus four variable

5.1.2. Case2: Four Control Variables Sets

Four control variables sets are used in this case are real power generation (Pg), generator voltage (Vg), the transformer tap changer (TAP) and the switchable VAR sources (Qc). The results after applying genetic algorithm are given in Table 2 and the voltage profile is shown in Fig 3. The optimization results are obtained and are compared with power flow results. The L-index value after load flow is 0.092369 and after applying OPF with GA is 0.047995 that means there is reduction of 48% in L-index.

Table 2 Control Variables Optimized Using Genetic Algorithm for 30-Bus System with Four Variables Sets

Control Variables	Load Flow Solution	L-index Minimized
PG_1	2.3923	2.3958
PG_2	0.5756	0.37925

PG_5	0.2456	0.34441
PG_8	0.35	0.33603
PG_{11}	0.1793	0.24966
PG_{13}	0.1691	0.30856
V_2	1.0338	1.1296
V_5	0.9814	1.0217
V_8	1.023	1.0501
V_{11}	1.0374	1.0897
V_{13}	0.9881	1.0837
t_1	0.978	1.075
t_2	0.969	1
t_3	0.932	1.1
t_4	0.968	1
Q_{24}	0	5
Q_{25}	0	2
Q_{26}	0	5
Q_{29}	0	5
Q_{30}	0	5
L-index	**0.092369**	**0.047995**

5.2. IEEE 57-BUS SYSTEM

The optimization problem using Genetic algorithm is also carried out on IEEE 57-bus system. 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, 4) where the respective value of L-index are given with the base case. From this computation it is found that Lmax = 0.13594 and the five weakest buses are selected (i.e. 30,31,32,33 and 34) whose L-index value is high. These five buses are selected for reactive power injection and the result of applying genetic algorithm are given in Table (III,IV).

5.2.1. Case1: Three Control Variables Sets

Three control variables sets for this case are generator voltage (Vg), the transformer tap changer (TAP) and the switchable VAR source (Qc). The applying Genetic algorithm is used for solving OPF problem and the results of applying GA are given in Table 3. The L-index after load flow is 0.13594 and after applying OPF with GA is 0.13244 so there is a reduction of 2.5% in L-index. The comparison between the voltages after the load flow and GA is shown in Fig 4.

Table3. Control Variables Optimized Using Genetic Algorithm for 57-Bus System with Three Variables Sets

Control Variables	**Load Flow Solution**	**L-index Minimized**
V_2	1.01	0.97602
V_3	0.985	1.0588
V_6	0.98	1.0318
V_8	1.005	1.045
V_9	0.98	1.0328
V_{12}	1.015	1.0434
t_1	0.97	1.1
t_2	0.978	1.1
t_3	1.043	0.9
t_4	1	0.92

t_5	1	1.1
t_6	1.043	0.94
t_7	0.967	1.1
t_8	0.975	1.1
t_9	0.955	1.1
t_{10}	0.955	1.1
t_{11}	0.9	1.1
t_{12}	0.93	1.1
t_{13}	0.895	1.1
t_{14}	0.958	1.1
t_{15}	0.98	0.9
t_{16}	0.94	0.9
t_{17}	0.958	1.02
Q_{30}	0.018	1
Q_{31}	0.029	1
Q_{32}	0.008	1
Q_{33}	0.019	1
Q_{34}	0	1
L-index	**0.13594**	**0.13244**

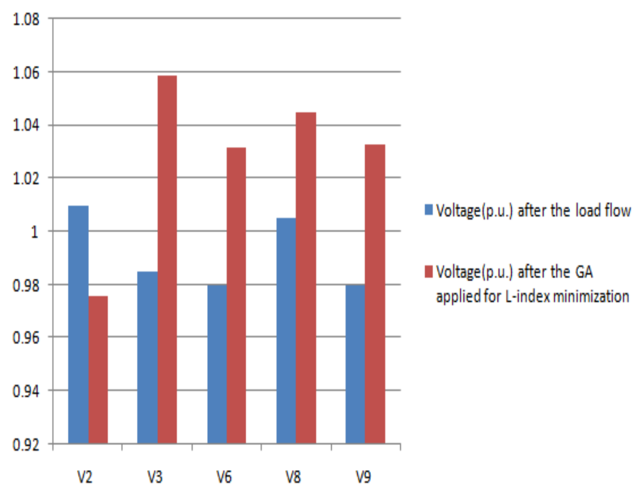

Fig. 4. Voltage profile of 57 Bus three variable

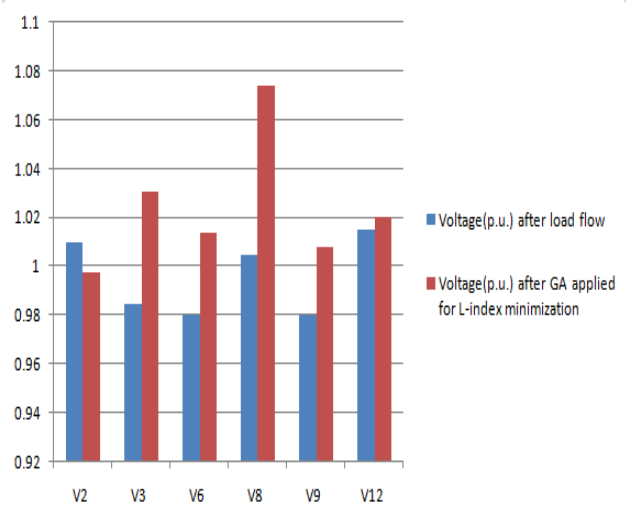

Fig. 5. Voltage profile of 57 Bus four variable

5.2.2. Case2: Four Control Variables Sets

Four control variables sets are used in this case are real power generation (Pg), generator voltage (Vg), the transformer tap changer (TAP) and the switchable VAR source (Qc). The results of applying GA are given in Table 4 and voltage profile for applying the GA is shown in Fig 5. Here, the L-index after the load flow is 0.13594 but after the application of OPF with GA the L-index are reduced to 0.1213, there is a reduction of 10.7%.

Control Variables	Load Flow Solution	L-index Minimized
PG_1	2.322	0.27562
PG_2	0.03	0.33462
PG_3	0.41	0.5047

PG_6	0.75	0.78745
PG_8	1.5	0.61526
PG_9	1.21	0.62465
PG_{12}	3.77	0.72814
V_2	1.01	0.99746
V_3	0.985	1.0304
V_6	0.98	1.0139
V_8	1.005	1.0742
V_9	0.98	1.008
V_{12}	1.015	1.0202
t_1	0.97	0.9
t_2	0.978	1.1
t_3	1.043	0.9
t_4	1	1.1
t_5	1	1.1
t_6	1.043	0.98
t_7	0.967	1.09
t_8	0.975	1.1
t_9	0.955	1.1
t_{10}	0.955	1.1
t_{11}	0.9	1.1
t_{12}	0.93	1.1
t_{13}	0.895	1.08
t_{14}	0.958	1.05
t_{15}	0.98	0.95
t_{16}	0.94	0.91
t_{17}	0.958	0.99
Q_{30}	0.018	1
Q_{31}	0.029	1
Q_{32}	0.008	1
Q_{33}	0.019	1
Q_{34}	0	1
L-index	**0.13594**	**0.1213**

VI. CONCLUSION

The objective of the problem is to improve the voltage stability in power system optimization with optimal value of L-index which controls and helps in improving the security enhancement problem. The system is considered having fitness function of L- index and optimized using Genetic Algorithm. GA is successfully applied for minimization of total objective function to improve results in power system optimization considering both testing system. The test system is applied for three and four variables in single objective function and providing far better results of power system optimization in four control variables as compared to three variable systems.

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