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Minimization of Power Loss and Voltage Deviation by SVC Placement Using GA

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Abstract

Modern restructured power systems sometimes operate with heavily loaded lines resulting in power system to work under condition of higher power loss and higher voltage deviation, which may result in insecure operation of power system; even sometimes it may lead to voltage instability or system collapse. It is mainly due to continuous and uncertain growth and demand of electrical power. This paper presents a methodology to solve a multi-objective optimization problem to find optimal location and size of Static VAR Compensator (SVC); in order to minimize real power loss (RPL)& load bus voltage deviation (VD) and also enhancing voltage securityusing Continuous Genetic Algorithm (CGA). The effectiveness of the proposed method is demonstrated on a standard IEEE 30-bus system. The results obtained reveal effectiveness of CGA in handling multi objective optimization problem efficiently and successfully.

***Keywords**: SVC, FACTS, RPL,Voltage Deviation, Real power loss, CGA*

1. Introduction

In last few years, voltage collapse problems in power systems have been an important issue for electric power utilities and a subject of great concern as the events of voltage instability and voltage collapses have occurred worldwide [1]. Voltage instability is one of the major causes of voltage collapse. Problem of improper reactive power planning may result in voltage instability and voltage collapse. Voltage instability is basically due to the lack of ability of a power system to maintain steady state voltages at all buses following a disturbance. While, voltage collapse is the process by which the sequence of events accompanying voltage instability leads to a blackout or abnormally low voltages in a considerable part of a power system [2].

The causes of voltage collapse may be faulted or heavily loaded transmission lines as well as insufficient supply and/or shortage of reactive power [2, 3].Reactive power Management is a key issue in electric power networks and shunt Flexible Alternating Current Transmission System (FACTS) devices may play a vital role in managing flow of the reactive power in electric power systems and, thus, the system voltage security and stability. Static Var compensator (SVC) is member of FACTS family which is connected in shunt with the system. FACTS family also includes Thyristor Controlled Series Compensations (TCSC), Unified Power Flow Controllers (UPFC) and Thyristor Controlled Phase Angle Regulators (TCPAR) etc. Although the main purpose of SVC is to support bus voltage by injecting (or absorbing) reactive power, it is also found competent for enhancing stability and security of the electric power networks [4-5]. FACTS devices can successfully control the power flows in the electric power network, reduce the power flow in heavily loaded lines, thus ensuing for

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an increased loadability, reduced system losses, improved system stability and reduced cost of production [5-9]. It is important to determine the optimal location of these devices due to huge investment.

Optimal location and size of different types of FACTS devices in the electric power network has been attempted with different objectives using different evolutionary techniques such as Genetic Algorithm (GA), hybrid tabu approach and simulated annealing (SA), *etc.* [10-15]. GA has been applied for finding the best location of a set of phase shifters for reducing power flows in heavily loaded lines which results in an increased loadability and reduced production cost [10]. For reducing the production cost including cost of the FACTS devices the best optimal location of FACTS is obtained using real power flow performance index [11]. The hybrid tabu search and simulated annealing has been implemented for minimizing the generator fuel cost in optimal power flow control using multi-type FACTS devices [12]. The optimal location of UPFC is found to minimize the generation cost function and the investment cost of UPFC using steady state injection model of UPFC, continuation power flow method and OPF technique [13]. Load flow algorithm is formulated and solved with TCSC and UPFC [14]. A hybrid GA is proposed for solving optimal power flow which includes FACTS devices in a power system [15]. A new multi-objective fuzzy-GA formulation is explored for optimal placement and size of shunt FACTS controllers [16]. Congestion management with FACTS application is discussed [17]. In [18], Huang *et al.* proposed optimal placement of SVC for the loadability of power systems. Mahmoudabadi and Rashidinejad *et al.* introduced an application of hybrid heuristic technique to find solution for expansion of concurrent transmission network and also for reactive power planning [19].

Non-Dominated Sorting PSO (NSPSO) has been proposed for optimal location of FACTS devices to maximize static voltage stability margin, minimize real power loss and voltage deviation [20, 21]. A Novel Global Harmony Search (NGHS) algorithm has been proposed and compared with harmony search (HS) algorithm and PSO for optimal placement of SVC and Statcom, for reduction in transmission losses, improvement in bus voltage profile. NGHS provided more accuracy, higher speed in finding better solution as compared to HS and PSO [22].A new Big Bang-Big Crunch (BB-BC) optimization algorithm has been applied for finding optimal size of FACTS for improvement of voltage stability limit, voltage profile and loss minimization under normal and line outage contingency conditions. The BIG BANG-BIG CRUNCH (BB-BC) optimization algorithm is similar to PSO needs fewer operators; therefore it is easy to apply for power system optimization problem. The BB-BC demonstrates better performance and convergence characteristics as compare to PSO [23].

This paper proposes a methodology for optimal location and size of SVC. This methodology consists of two parts one of it identifies severity of line using voltage power index (*VPI*), and in the another part CGA has been implemented following these critical line outages to find optimal location and size of SVC for minimization of real power loss and load bus voltage deviation and also to enhance voltage security accounting equality & inequality constraints. Section 2 describes problem formulation. Section 3 presents an overview of CGA technique. Section 4 presents implementation of the CGA technique for optimizing multi-objective functions. Section 5 gives Case study, results and discussions. Concluding remarks are presented in Section 6.

2. Problem Formulation

For optimal placement of SVC in a power system, single line outages are considered as contingencies in this paper and to evaluate the severity of a contingency, Voltage Power Index (*VPI*) [26] has been used as:

$$VPI = \sum_{i=1}^{NB}(\Delta|V_{i|}/\Delta\,|\,V_i^{max}|)^{2m} \quad (1)$$

where $NB$is number of buses, $\Delta|\mathrm{V_i}|$is the difference between the voltage magnitude in line outage condition and base case condition;$\Delta|\mathrm{V_i^{max}}|$ is the value set by the utility engineers to indicatetolerable limit for an outage case. Optimal location and size of SVC device has been determined to minimize real power loss and to reduce load bus voltage deviation from its nominal value 1.0 p.u. The values of NB,$\Delta|\mathrm{V_i^{max}}|$ and exponent *m* have been considered as 30, 0.2 and 2 respectively.

2.1 Minimization of real power loss

The first objective function f_1 can be defined as

$$P_L = \sum_{k=1}^{NTL}[g_k[V_i^2 + V_j^2 - 2V_i\,V_j\cos(\delta_i - \delta_j)] \quad (2)$$

where, NTL is the number of transmission lines; g_k is the conductance of k^{th} line; $V_i\angle\delta_i$ and $V_j\angle\delta_j$are the voltages at the end buses *i* and *j* of k^{th}line, respectively.

2.2 Minimization of Voltage Deviations

In a power system, it is desirable to maintain the load bus voltages within specified deviation limits usually within ±5% of the nominal value. In this work, the optimal location and size of SVC is determined such that voltage deviations is minimum. Thus, the second objective function f_2 for minimization of load bus voltage deviation (VD) can be defined as

$$VD = \sum_{k=1}^{NL}|(V_k - V_k^{ref})| \quad (3)$$

2.3 Multi-objective function

A general multi-objective optimization problem consists of a number of objectives to be optimized simultaneously. In this work, the multi-objective problem is converted to a single objective optimization problem by linear combination of real power transmission loss and load bus voltage deviation objectives as follows:

$$\text{Ƒ}(u,v) = w_1 \times f_1(u,v) + w_2 \times f_2(u,v) \quad (6)$$

Where, Ƒ (u,v) is the weighted sum of real power loss and load bus voltage deviation objective functions, which are combined to form single objective function using weighing factor w. In this study w_1 is varied between 0 and 1, and w_2=1-w_1.

2.4 Constraints

Above multi-objective functionsare optimized subject to following constraintsunder current operating condition as well as next predicted loading condition.

2.4.1 Equality Constraints

The equality constraints represent the typical load flow equations as follows:

$$P_{Di} - V_i\sum_{j=1}^{NB}V_j[G_{ij}\cos(\delta_i - \delta_j) + B_{ij}\sin(\delta_i - \delta_j))] = 0 \quad (7)$$

for i = 1,……., *NB*

$$Q_{Gi-}Q_{Di} - V_i\sum_{j=1}^{NB}V_j[G_{ij}\sin(\delta_i - \delta_j) - B_{ij}\cos(\delta_i - \delta_j)] = 0 \quad (8)$$

for i = 1,……., *NB*

where, NB is the number of buses; P_{Gi} and Q_{Gi} are the generator real and reactive power at bus i, respectively; P_{Di} and Q_{Di} are the load real and reactive power at bus i respectively; G_{ij} and B_{ij} are the transfer conductance and susceptance between bus i and bus j, respectively.

2.4.2 Inequality Constraints

(i) Active power generation constraint:

$$\underline{P}_{gi} \leq P_{gi}^{o} \leq \overline{P}_{gi}$$
$$\underline{P}_{gi} \leq P_{gi}^{p} \leq \overline{P}_{gi} \qquad (4)$$
$$i = 1,2,..., NG$$

(iv) Reactive power generation constraint:

$$\underline{Q}_{gi} \leq Q_{gi}^{o} \leq \overline{Q}_{gi}$$
$$\underline{Q}_{gi} \leq Q_{gi}^{p} \leq \overline{Q}_{gi} \qquad (5)$$
$$i = 1,2,..., NG$$

(v) Inequality constraint on load bus voltages:

$$\underline{V}_{k} \leq V_{k}^{o} \leq \overline{V}_{k}$$
$$\underline{V}_{k} \leq V_{k}^{p} \leq \overline{V}_{k} \qquad (6)$$
$$k = NG + 1.........NB$$

3. Continuous Genetic Algorithm (CGA)

The CGA is very similar to binary GA [24-25]. The primary difference is the fact that variables in CGA are no longer represented by bits of zero and ones, but represented by floating-point numbers of desired appropriate range. The CGA has benefit of requiring less memory storage and utilize full machine precision than binary GA because a single floating–point number represents the variable instead of N_{bits} integers. The CGA is faster, as compared to binary GA, because the chromosomes do not have to be decoded prior to evaluation of cost function. The flow chart of the CGA is shown in Figure 1. Description of blocks is as follows [24-25]:

Continuous Genetic Algorithm (CGA) is a generalized search and optimization technique inspired by the theory of biological evolution. CGA maintains a population of individuals that represent candidate solutions. Each individual is evaluated to give some measure of its fitness to the problem from the objective function. In each generation, a new population is formed by selecting the more fit individuals based on a particular selection strategy. Some members of the new population undergo genetic operations to form new solutions. The two commonly used genetic operations are crossover and mutation. Crossover is a mixing operator that combines genetic material from selected parents. Mutation acts as a background operator and is used to search the unexplored search space by randomly changing the values at one or more positions of the selected chromosome.

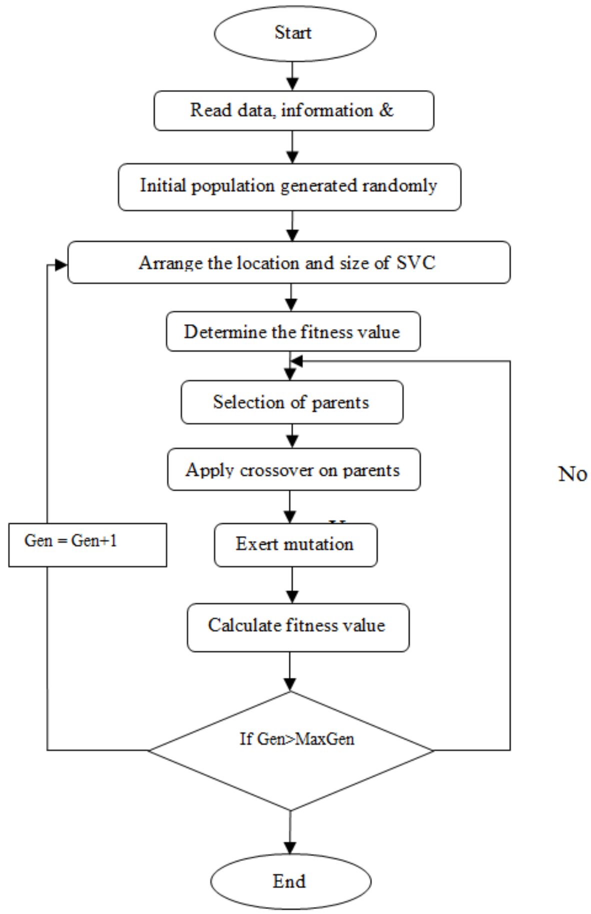

Figure 1. Fundamental Flowchart of Continuous GA

4. Methodology for Finding the Optimal Location and Size of SVC

The computational steps used for implementation of CGA for obtaining the optimal location and size of SVC s are as follows

1. Simulate various single line outages and for each outage run Newton Raphson (NR) power flow program to compute *VPI* for each outage using (1).
2. On the basis of *VPI*, rank various contingencies in order of their severity.
3. Starting from the most severe contingency, apply continuous GA to find optimal location and size of SVC for minimization of real power loss and voltage deviation. CGA program is being run for 21 trials with initial value of w_2=0 (i.e. for power loss only) and varied in step of 0.05 until value of w_1 becomes equal 1 (i.e. voltage deviation only).
4. Place SVC of computed rating at the location obtained from step 3 and analyzes voltage profile, real power losses, and load bus voltage deviation.
5. For SVC of selected rating placed at any selected location, simulate various contingencies and examine the voltage profiles, real power loss and voltage deviation for each line outage.

6. Repeat steps 4 to 5 for different size and location of obtained from step 3.
7. Find out the best optimal location and optimal size for the placement SVC by comparing the voltage security, real power loss and load bus voltage deviation.

4.1 Implementation steps of CGA following by critical line outage

Step-1: Data input: System data and constraints.

Step-2: Base case load flow solution is obtained using Newton Raphson methodology.

Step-3: Evaluate the voltage performance index (*VPI*) by single line outages using relation (1).

Step-4: On the basis of *VPI*, rank various contingencies in order of their severity.Run CGA program following by outage of critical line one by one.

- **(a) Initialization**; Generate population of size ‘M’ (no. of load buses) for SVC placement. Generated population is uniformly distributed in the range

$$\underline{U}_{ij} < U_{ij} < \overline{U}_{ij} \;.\; j = 1,2,...,NC$$
$$U_i^0 = [u_{i1}^0, u_{i2}^0, u_{i3}^0, ..., u_{i,NC}^0]^T$$

- **(b) Run** Newton Raphson power flow program for each vector of the population.
- **(c)** Calculate objective function.
- **(d)** Set generation count $k = 1$.
- **(e)** Select f(t) from f(t-1) by any selection process like roulette wheel selection, tournament selection, ranking selection etc.
- **(f)** Apply crossovers.
- **(g)** Apply mutation. Mutation changes randomly the new offspring.The mutation operator is used to inject new genetic material into the population.
- **(h)** Increase generation count $k = k + 1$.
- **(i)** If $k \le k_{\max}$ repeat from **(e)** to **(g)** Otherwise stop.

5. Case Studies

In order to establish the effectiveness of the proposed Continuous Genetic Algorithm, it has been implemented on IEEE 30 bus system for finding optimal location and size of SVC [25]. This system comprises of one slack bus, 5 *PV* buses, 24 *PQ* buses and 41transmission lines. For optimal placement of SVC, single line outages are considered as contingencies in the test power system and to evaluate the severity of a contingency, Voltage Power Index (*VPI*) has been used.

It has been observed that NR load flow converges for 37 line outages out of 41 line outages. The ranking of critical contingencies on the basis of *VPI* values is as 36, 5, 38, 4, 9, 37, 26, 11 and so on. In this work four most critical contingencies i.e. outage of line no. 36, 5, 38 and 4 have been considered for the placement of SVC.

5.1 Optimal location and optimal size of SVC

The line outage contingency in order of *VPI* i.e. line no. 36, 5, 38 and 4 are considered one by one to find optimal location and size of SVC for minimization of objective function Ƒ (*u*,*v*).The continuous genetic algorithm program has been run for 1500 generations, considering all 24 *PQ* buses as possible location for placement of SVC and SVC size varying from -1 p.u. to 1 p.u. Initially the value of w_2 is taken zero (power loss only) which varied in step of 0.05 until w_2 becomes 1(load bus voltage deviation only). The simulation result obtained, gives a set of 21 trials for each of line outage which include optimal location and size of SVC, real power loss, load bus voltage deviation and value of w_1. Due to limited space, this set of 21 trials obtained for outage of line no. 36 is only shown in Table 1.

Table 1. Results of CGA for outage of Line no.36

Trial No.	Optimal Location	Optimal Size in p.u.	Real Power Loss in p.u.	Voltage Deviation in p.u.	w_1
	30	-0.06756	0.19349	0.72783	1
	30	-0.06724	0.19349	0.72869	0.95
	30	-0.06687	0.1935	0.72968	0.9
	30	-0.06717	0.19349	0.72886	0.85
	30	-0.06865	0.19348	0.72486	0.8
	30	-0.06689	0.1935	0.72963	0.75
	30	-0.069	0.19348	0.72393	0.7
	30	-0.06724	0.19349	0.72868	0.65
	30	-0.06728	0.19349	0.72857	0.6
	30	-0.06703	0.1935	0.72925	0.55
	30	-0.06769	0.19349	0.72746	0.5
	30	-0.06724	0.19349	0.72868	0.45
	30	-0.07017	0.19347	0.72075	0.4
	30	-0.06727	0.19349	0.7286	0.35
	30	-0.06695	0.1935	0.72947	0.3
	30	-0.06765	0.19349	0.72758	0.25
	30	-0.06691	0.1935	0.72959	0.2
	30	-0.06794	0.19349	0.72678	0.15
	30	-0.06717	0.19349	0.72889	0.1
	30	-0.06728	0.19349	0.72858	0.05
	30	-0.06759	0.19349	0.72774	0

From Table 1, itcan be observed that optimal location and size of SVC obtained in the trial no. 13 for w_1=0.4, where real power loss and voltage deviation both are found lowest. The set of 21 trials obtained as results of CGA program for simulating each of the four critical contingency one by one.Theoptimal values are selected and summarized in Table 2. The convergence characteristics of continuous genetic algorithm for outage of line no. 36 have been shown in Figure 2 and Figure 3 for w_1=1(power loss only) and w_2=1 (voltage deviation only) respectively. Thedeveloped optimization program using CGA also computes value of voltage magnitude at all the buses.

Table 2. Summarized Results of CGA

Line Outage	Optima l Location	Optimal Size in p.u	Real Power Loss in p.u	Voltage deviation in p.u	w_1
LO 36	30	-0.07017	0.19347	0.72075	0.4
LO 5	12	0.56087	0.33559	0.22307	0.3 5
LO 38	30	-0.00964	0.18088	0.68253	0.2
LO 4	12	0.55855	0.26746	0.27719	0.3 5

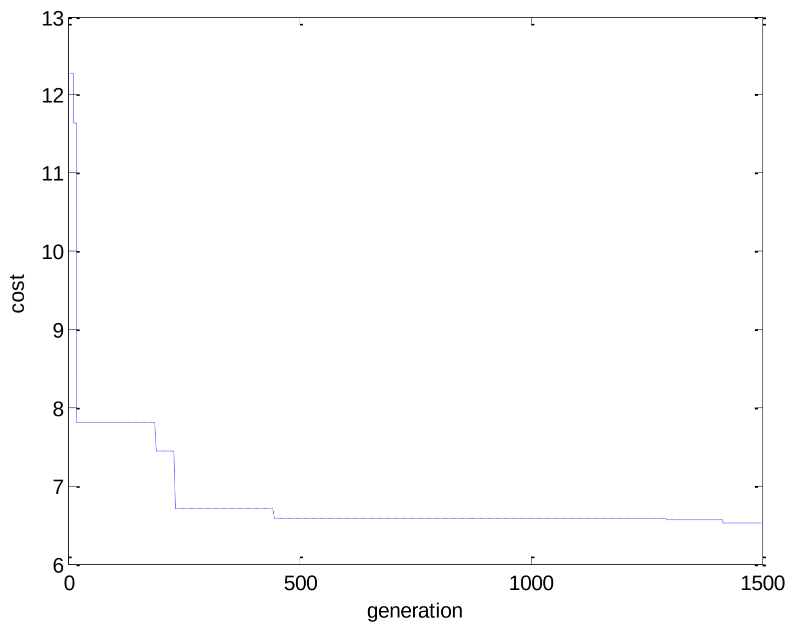

Figure 2. Convergence Characteristics of CGA for Power Loss Minimization with LO 36

As can be observed from Table 2, for outage of line nos. 36 and 38, the optimal location of SVC is found bus no. 30 while for outage of line nos. 5 and 4; the optimal location of SVC is obtained bus no.12. The bothSVCsobtained for bus no. 12 work in inductive mode at and absorb reactive power from the system whereas both of it workin capacitive mode at bus no. 30 and supplies reactive power to the system.

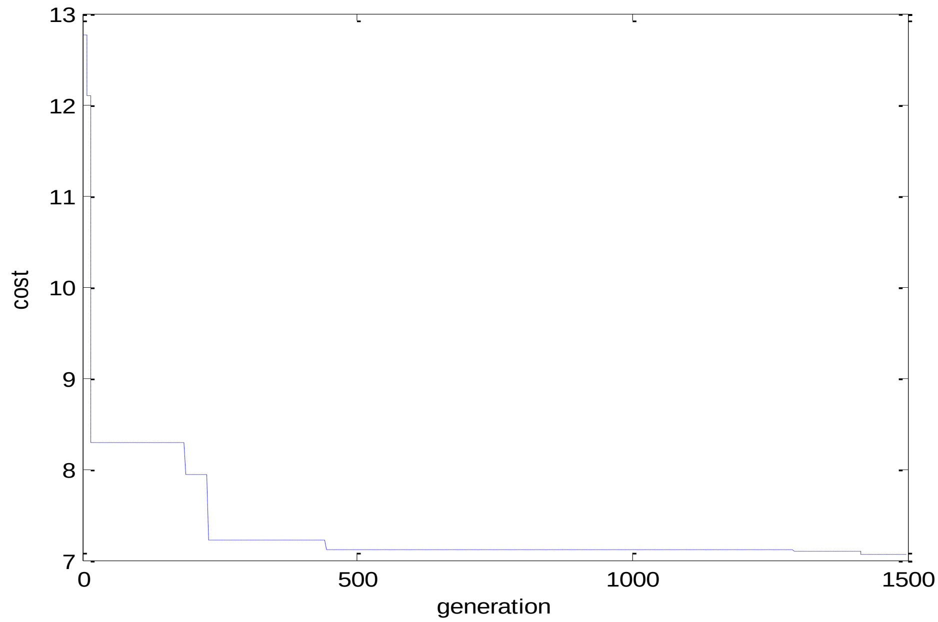

Figure 3. Convergence Characteristics CGA for Voltage Deviation Minimizationwith LO 36

5.2 Analysis of voltage security after placement of SVC

As can be observed from Table 2, the two possible optimal rating of SVC are computed for bus no. 12. The SVC of these different rating, *i.e.*, 0.56087 p.u. and 0.55855 p.u. is placed at bus no. 12 one by one. The developed NR load flow program is run to compute voltage of all thebuses before and aftersingle line outage contingency. It is found that with placement of SVCs as obtained for bus no.12one by one, both of the SVCs work in inductive mode and absorbs reactive power of system.Placement of these SVCs one by one resultsinstead of improving, poor voltage magnitude profile. Even at some of the buses voltage magnitude becomes less as compare to base case. Therefore, SVC of either 0.56087 p.u. or 0.55855 p.u. at bus no. 12 cannot be a good choice and/or possible optimal location for SVC placement as far as voltage security is concerned.

Table 2 also depicts two possible optimal rating of SVCs, *i.e.*, -0.00964 p.u. and -0.07017 p.u. for bus no. 30. After placement of SVCs as obtained for bus no. 30, critical line outages are simulated considering one at a time. It is found from developed NR load flow program that both SVCs are working in capacitive mode. The SVC of -0.00964 p.u. however capacitive in nature and supplies reactive power to system but it proves small in size for maintaining voltage 1 p.u. at all the buses after single line outage contingency, specially for outage of line no. 36. The Placement of SVC of -0.07017 p.u. is found a good choice as it maintains voltage at all buses 1 p.u. or nearly 1 p.u. before and after severe single line outage contingency.

Voltage magnitude at all buses for base case and for outage of line no 36 and line no. 5, without and with SVC of -0.07017 p.u. at bus no. 30 is shown in Table 3. It can be observed from Table 3 that voltage at bus no. 25, 26, 27, 29 and 30 for line outage 36 was very less which after placement of the SVC at bus no. 30 becomes 1 p.u. except bus no.30 (0.9555).

Similarly, voltage profile at all the buses for outage of line no. 5 is also improved by this SVC placement at bus no. 30.

Table 3. Voltage Profile for Base Case, LO 36, LO 5 Without and With SVC at Bus No. 30

Bus No.	Voltage Profile at Base Case	Line Outage 36		Line Outage 5	
		Without SVC	With SVC at bus no. 30	Without SVC	With SVC at bus no. 30
	1.0600	1.0600	1.0600	1.0600	1.0600
	1.0430	1.0430	1.0430	1.0430	1.0430
	1.0215	1.0201	1.0209	1.0153	1.0159
	1.0129	1.0112	1.0121	1.0062	1.0070
	1.0100	1.0100	1.0100	1.0100	1.0100
	1.0121	1.0115	1.0123	1.0068	1.0078
	1.0034	1.0031	1.0036	0.9963	0.9969
	1.0100	1.0100	1.0100	1.0100	1.0100
	1.0510	1.0461	1.0498	1.0477	1.0492
	1.0444	1.0354	1.0425	1.0402	1.0428
	1.0820	1.0820	1.0820	1.0820	1.0820
	1.0574	1.0530	1.0564	1.0551	1.0564
	1.0710	1.0710	1.0710	1.0710	1.0710
	1.0424	1.0353	1.0404	1.0400	1.0419
	1.0378	1.0270	1.0334	1.0348	1.0372
	1.0447	1.0382	1.0432	1.0414	1.0433
	1.0391	1.0309	1.0373	1.0352	1.0376
	1.0279	1.0177	1.0244	1.0245	1.0270
	1.0253	1.0154	1.0222	1.0215	1.0241
	1.0293	1.0196	1.0265	1.0254	1.0280
	1.0321	1.0182	1.0276	1.0279	1.0313
	1.0327	1.0173	1.0273	1.0285	1.0322
	1.0272	1.0045	1.0165	1.0238	1.0281
	1.0216	0.9835	1.0029	1.0176	1.0244
	1.0189	0.9246	0.9706	1.0143	1.0300
	1.0012	0.9051	0.9520	0.9966	1.0125
	1.0257	0.8999	0.9626	1.0209	1.0419
	1.0107	1.0152	1.0158	1.0067	1.0095
	1.0059	0.8770	0.9539	1.0010	1.0340
	0.9945	0.8637	0.9555	0.9895	1.0355

Due to limited space, instead of presenting voltage magnitude in tabular form,computed from developed NR load flow program for outage of line no. 38 and line no. 4, withoutand with SVC at bus no. 30, the voltage magnitude graphs are shown in Figure 3 and Figure 4. It can be observed from the Figure 3 and Figure 4 that placement of SVC (-0.07017 p.u.)at bus no. 30 is also capable to maintain voltage magnitude within specified limit, even outage of line no. 38 or line no. 4 is occur one at a time.

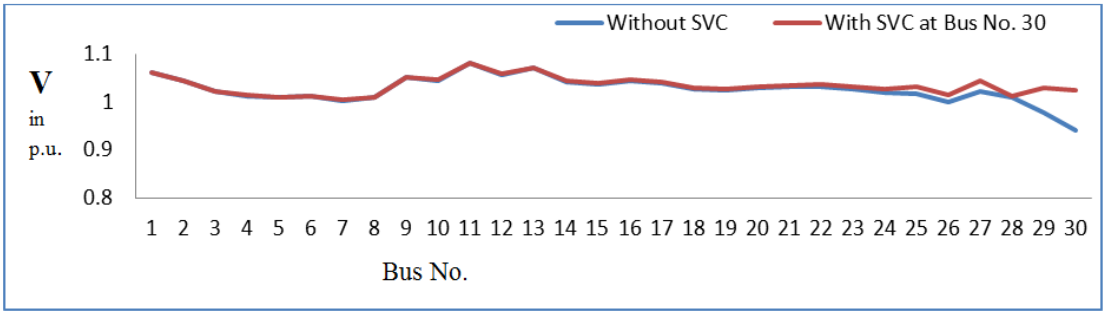

Figure 3. Outage of Line No. 38

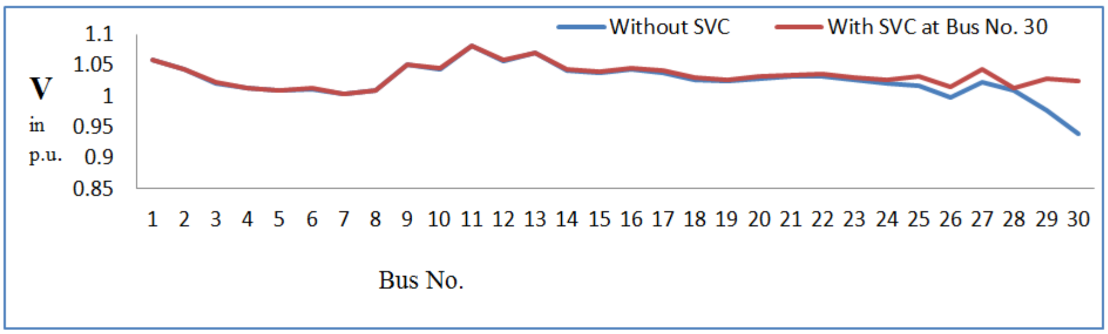

Figure 4. Outage of Line No. 4

5.3 Results and Discussion

The SVCs of different ratings and their respective optimal location as computed from the developed CGA program are compiled in Table 2. After placing these SVCsone by one at their respective optimal location the real power loss and load bus voltage deviation obtained in p.u. are also shown in Table 2. At the same time for all placements of SVCs voltage security of the system is also analyzed. The placement of SVCs one by one is compared forminimization of real power loss, load bus voltage deviation and for voltage security as well. It is observed that with placement of the SVC of -0.07017 p.u. at bus no. 30 is capable to maintain voltage security of the system for outages of all critical lines occurring one at a time. The placement of this SVC also provides optimal real power loss and optimal load bus voltage deviation. The optimal real power loss and optimal load bus voltage deviation found with this placement of the SVC is 0.19347 p.u. and 0.72075 p.u., respectively.

Authors have also simulated this optimization with one and more than one SVC shown in Table 2 for base case and critical single line outage contingencies but it is found that only one SVC of the selected rating is enough to optimize the goal and to maintain voltage security of the system before and after critical single line outage.

6. Conclusion

In this paper, optimal location and size of SVC have been computed in order to minimize real power loss and load bus voltage deviation using continuous GA.Analysis of Voltage magnitude profile is also done at the same time to notice its effect in maintaining voltage security of the system. The problem is formulated as multi-objective optimization problem. The proposed CGA has been implemented on standard IEEE 30-bus test system, which indicates that proposed method is able to provide optimal location and size of SVC for multi-objective optimization. Though, the proposed approach has been implemented on IEEE 30-bus test system, the same can be implemented on practical power system as well.

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