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ENHANCEMENT OF VOLTAGE STABILITY AND REDUCTION OF POWER LOSS USING GENETIC ALGORITHM THROUGH OPTIMAL LOCATION OF SVC, TCSC AND UPFC

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Abstract

Due to huge increase in power demand, power system network will lead to major problems such as voltage instability and voltage collapse in the power system. To overcome these problems, Flexible AC Transmission System (FACTS) devices have been implemented in power system. By placing these devices in suitable locations, the power system can be operated far away from the instability point. In this paper, the optimal location and the ratings of FACTS devices such as Thyristor Controlled Series Capacitor (TCSC), Static VAR Compensator (SVC) and Unified Power Flow Controller (UPFC) are determined using Genetic Algorithm (GA). A multi objective optimization problem is formulated with the consideration of minimizing voltage stability index, real power loss and generator cost. Evolutionary algorithm such as GA is a population based search method is used for solving multi objective optimization problem that is capable of searching for multiple solutions concurrently in a single run and provide an optimal solution. It is observed from the results that the voltages stability index, real power loss and generator cost are reduced by optimally locating the FACTS devices in the power system. IEEE 14 bus and IEEE 57 bus systems are used to demonstrate the effectiveness of the proposed algorithm.

Keywords: Voltage stability, Voltage collapse, SVC, TCSC, UPFC, GA.

1. Introduction

Power system networks are widely interconnected and operated under heavily stressed conditions due to increase in power demand. In some cases, the generating station is far away from the load centre and it is a critical task to transmit the power over longer distance to huge loads and this will cause more real power losses and voltage instability as in [1-3]. Voltage stability is defined as

Nomenclatures

a_i	Cost coefficient of i^{th} generator ($/MWh^2)
$B_{i,j}$	*Susceptance of line i-j*
B_{SVC}	*Susceptance value of SVC*
b_i	Cost coefficient of i^{th} generator ($/MWh)
C_{ji}	*Elements of matrix C*
c_i	Cost coefficient of i^{th} generator
F_i	Objective function i
$G_{i,j}$	Conductance of line i-j
h_i	Weighting factor of i^{th}objective function
I_G	Current at generator bus
I_L	Current at load bus
L_j	Voltage stability index value of load bus j
N_L	*Total number of transmission lines*
n	Number of generators
P_i	Real power at bus i
P_{loss}	Real power loss
Q_i	Reactive power at bus i
$\|V_i\|$	*Voltage magnitude of bus i*
X_C	Nominal reactance of the fixed capacitor
X_L	Nominal reactance of the TCR
X_{Line}	Reactance of the transmission line i-j
Y_{ij}	Bus admittance matrix element i,j

Greek Symbols

α	Angle of advance
α_G	*Set of generator buses*
α_L	*Set of load buses*
β	Firing angle
δ_i	Voltage angle at bus i
$\theta_{i,j}$	Angle of bus admittance matrix element i,j

Abbreviations

FACTS	Flexible AC Transmission System
GA	Genetic Algorithm
SVC	Static VAR Compensator
TCSC	Thyristor Controlled Series Capacitor
UPFC	Unified Power Flow Controller

the ability of a power system to maintain steady voltages at all the buses in the system after being subjected to a disturbance from a given initial operating condition. In recent years, voltage instability has been responsible for several major network collapses. Several incidences of voltage collapse have been reported, in different parts of the country as in [4]. Recent developments in power electronics introduced several control devices such as FACTS (Flexible AC Transmission System). Insertion of FACTS devices in transmission line will provide many advantages. The phase angle, the voltage magnitude and line impedances of the transmission line are the three main parameters that can be controlled by FACTS devices in an effective manner as in [5].

Genetic Algorithm was first developed by John Holland, University of Michigan in 1970's. It can able to solve multi objective optimization problems and gives optimal solution by iterations, which maintains a constant size population of candidate solutions. During each iteration, three genetic operators such as selection, crossover, and mutation are performed to generate new population and chromosomes of the new population are evaluated via the value of the fitness. Based on these genetic operators and the evaluations, the better new populations of candidate solution are formed from the old population. If the search goal has not been achieved, again GA creates offspring strings through three operators and the process is continued until the search goal is achieved as in [6].

Soft computing techniques can be used to solve multi objective optimization problem efficiently and effectively. FACTS devices can be located optimally by soft computing techniques such as Genetic Algorithm (GA) as in [7]. The location and the parameter settings of SVC, TCSC and UPFC can be optimized and the system performance can be enhanced as in [8-12]. This paper investigates the detailed application of GA to find the optimal location and ratings of SVC, TCSC and UPFC to enhance the voltage stability and reduce the power losses and the power generation cost.

2. Problem Formulation

In this paper, the problem is formulated which includes the minimization of voltage stability index, generation cost and real power loss. A multi-objective optimization problem consists of multiple objectives to be optimized simultaneously with the various equality and inequality constraints. Better results can be obtained by minimizing the objective function and satisfying all the constraints as in [11].Three objectives such as minimization of voltage stability index, generation cost and real power loss are combined and obtainedmulti-objective optimization problem.

2.1. Voltage stability index

Voltage stability is an important problem to electric power system. An indicator L-index is used to evaluate voltage stability at each bus of the system as in [12]. L index at load bus j can be expressed as given in Eq. (1) and matrix C can be found using Eq. (2)

$$L_j = |L_j| = \left|1 - \frac{\sum_{i\in\alpha_G} C_{ij} V_i}{V_j}\right| \quad j \in \alpha_L \tag{1}$$

$$[C] = -[Y_{LL}]^{-1}[Y_{LG}] \tag{2}$$

Matrices $[Y_{LL}]$ and $[Y_{LG}]$ can be found using Eq. (3).

$$\begin{bmatrix} I_L \\ I_G \end{bmatrix} = \begin{bmatrix} Y_{LL} & Y_{LG} \\ Y_{GL} & Y_{GG} \end{bmatrix} \begin{bmatrix} V_L \\ V_G \end{bmatrix} \tag{3}$$

The objective function considering minimization of voltage stability index can be represented as given in Eq. (4).

$$F_1 = L_{max} = max(L_j)\ j \in \alpha_L \tag{4}$$

2.2. Fuel cost of generators

The objective function considering minimization of generation cost as in [13] can be represented as given in Eq. (5).

$$F_2 = F(P_G) = \sum_{i=1}^{n} a_i P_{Gi}^2 + b_i P_{Gi} + c_i \tag{5}$$

2.3. Real power loss

The objective function considering minimization of real power loss as in [14] can be represented as given in Eq. (6).

$$F_3 = P_{loss} = \sum_{i=1}^{N_L} G_{i,j}(V_i^2 + V_j^2 - 2V_i V_j cos(\delta_i - \delta_j)) \tag{6}$$

2.4. Fitness function

Considering all the objective functions (4)-(6), the fitness function or net objective function is expressed as given in Eq. (7).

$$F = h_1F_1 + h_2F_2 + h_3F_3 \tag{7}$$

where $h_{1,}$ h_2 and h_3 are weighting factor of voltage stability index objective function, weighting factor of fuel cost objective function, weighting factor of power loss objective function respectively as in [15].

$$h_1 + h_2 + h_3 = 1 \tag{8}$$

The coefficients $h_{1,}$ h_2 and h_3 are optimized by trial and error method to 0.35, 0.35 and 0.3 by satisfying Eq. (8).

3. FACTS Devices

The concept of FACTS controllers was first defined by Hingorani in 1988. FACTS devices have the ability to control the various electrical parameters such as the phase angle, the voltage magnitude at chosen buses and line impedances of transmission system. Introduction of FACTS devices will provide advantages such as power flow control, managing blackouts, enhancing voltage stability, limiting short circuit currents as in [16-17]. FACTS can be classified into four categories namely series, shunt, combined series-series and combined series-shunt controllers. This paper deals with a shunt controller (SVC), a series controller (TCSC), and a combined series-shunt controller (UPFC).

3.1. Power flow modelling of SVC

Static Var Compensator (SVC) behaves like a shunt connected variable reactance, which either generates or absorbs reactive power in order to regulate the voltage magnitude at the point of connection to the AC network. It is extensively to provide fast reactive power and voltage regulation support. The basic model of SVC is shown in Fig. 1.

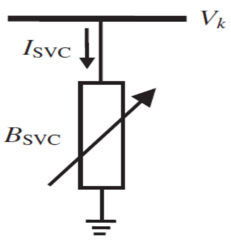

Fig. 1. Basic model of SVC.

The SVC can be inserted in the bus or at the midpoint of the transmission line. The current drawn by the SVC is given in Eq. (9).

$$I_{SVC} = jB_{SVC}V_k \quad (9)$$

The reactive power drawn by the SVC, which is also the reactive power injected at bus k, is given in Eq. (10).

$$Q_{SVC} = Q_k = -V_k^2 B_{SVC} \quad (10)$$

The range of reactive power generation of SVC is limited between -25 MVAR and +25 MVAR.

3.2. Power flow modelling of TCSC

Thyristor-controlled series compensators (TCSC) is a series connected FACTS device. It reduces the power flow in heavily loaded line by controlling the power flow in the network. It is able to minimize the power loss of the systems. The basic model of TCSC is shown in Fig. 2.

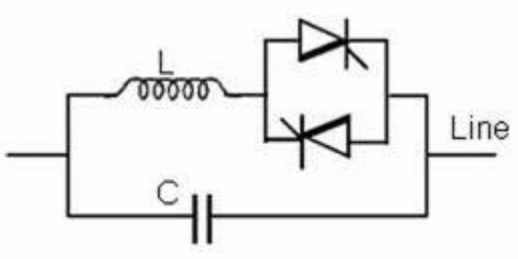

Fig. 2. Basic model of TCSC.

In this FACTS device, a capacitor is inserted in series with the transmission line to be compensated and a Thyristor Controlled Reactor (TCR) is connected in parallel with the capacitor. Net reactance of the transmission line can be found by Eq. (11) and the rated value of TCSC can be found by Eq. (12).

$$X_{ij} = X_{Line} + X_{TCSC} \quad (11)$$

$$X_{TCSC} = X_C - \frac{X_C^2}{(X_C - X_L)}\frac{2\beta + sin2\beta}{\pi} + \frac{4X_C^2}{(X_C - X_L)}\frac{cos^2\beta(ktank\beta - tan\beta)}{(k^2-1)\pi} \quad (12)$$

$$B = \pi\text{-}\alpha;\ k = \sqrt{\frac{X_C}{X_L}}$$

The range of TCSC reactance is limited between -50% X_{Line} and +50% X_{Line}

3.3. Power flow modelling of UPFC

The UPFC consists of two switching converters operated from a common DC link. Series converter injects an AC voltage with controllable magnitude and phase angle in series with the transmission line. Shunt converter injects or absorbs an independently controllable reactive power to bus. It also supplies or absorbs the active power demanded by series converter through the common DC link. UPFC equivalent circuit is shown in Fig. 3.

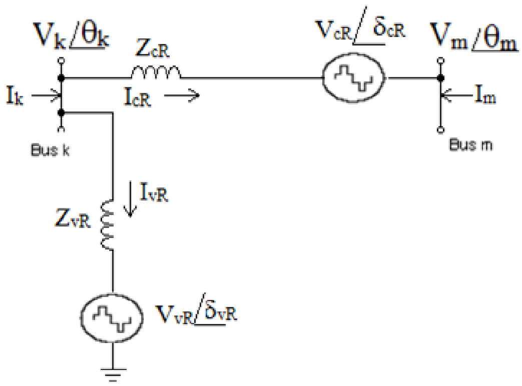

Fig. 3. UPFC equivalent circuit.

The output voltage of the series converter is added to the nodal voltage at bus k to increase the nodal voltage at bus m. The voltage magnitude of the output voltage V_{cR} provides voltage regulation, and the phase angle δ_{cR} determines the mode of power flow control. In addition to providing a supporting role in the active power exchange that takes place between the series converter and the AC system, the shunt converter generate or absorb reactive power in order to provide independent voltage magnitude regulation at its point of connection with the AC system.

From the equivalent circuit of UPFC the active and reactive power equations can be written as given in Eqs. (13-20).

At bus *k*:

$$P_k = V_k^2 G_{kk} + V_k V_m [G_{km} cos(\theta_k - \theta_m) + B_{km} sin(\theta_k - \theta_m)] + V_k V_{CR} [G_{km} cos(\theta_k - \delta_{CR}) + B_{km} sin(\theta_k - \delta_{CR})] + V_k V_{VR} \quad (13)$$

$$Q_k = -V_k^2 B_{kk} -$$

$$V_kV_m[G_{km}sin(\theta_k - \theta_m) - B_{km}cos(\theta_k - \theta_m)] + V_kV_{CR}[G_{km}sin(\theta_k - \delta_{CR}) - B_{km}cos(\theta_k - \delta_{CR})] + V_kV_{VR}[G_{VR}sin(\theta_k - \delta_{VR}) - B_{VR}cos(\theta_k - \delta_{VR})] \quad (14)$$

At bus *m*:

$$P_m = V_m^2G_{mm} + V_mV_k[G_{mk}cos(\theta_m - \theta_k) + B_{mk}sin(\theta_m - \theta_k)] + V_mV_{CR}[G_{mm}cos(\theta_m - \delta_{CR}) + B_{mm}sin(\theta_m - \delta_{CR})] \quad (15)$$

$$Q_m = -V_m^2B_{mm} + V_mV_k[G_{mk}sin(\theta_m - \theta_k) - B_{mk}cos(\theta_m - \theta_k)] + V_mV_{CR}[G_{mm}sin(\theta_m - \delta_{CR}) - B_{mm}cos(\theta_m - \delta_{CR})] \quad (16)$$

Series converter

$$P_{CR} = V_{CR}^2G_{mm} + V_{CR}V_k[G_{km}\,cos(\delta_{CR} - \theta_k) + B_{km}sin(\delta_{CR} - \theta_k)] + V_{CR}V_m[G_{mm}\,cos(\delta_{CR} - \theta_m) + B_{mm}sin(\delta_{CR} - \theta_m)] \quad (17)$$

$$Q_{CR} = -V_{CR}^2B_{mm} + V_{CR}V_k[G_{km}\,sin(\delta_{CR} - \theta_k) - B_{km}cos(\delta_{CR} - \theta_k)] + V_{CR}V_m[G_{mm}\,sin(\delta_{CR} - \theta_m) - B_{mm}cos(\delta_{CR} - \theta_m)] \quad (18)$$

Shunt converter

$$P_{VR} = -V_{VR}^2G_{VR} + V_{VR}V_k[G_{VR}\,cos(\delta_{VR} - \theta_k) + B_{VR}sin(\delta_{VR} - \theta_k)] \quad (19)$$

$$Q_{VR} = V_{VR}^2B_{VR} + V_{VR}V_k[G_{VR}\,sin(\delta_{VR} - \theta_k) - B_{VR}cos(\delta_{VR} - \theta_k)] \quad (20)$$

4. Genetic Algorithm

In the artificial intelligence, GA is a search heuristic that mimics the process of natural selection which was developed by John Holland in 1970, university of Michigan. This method is an iterative procedure used to generate optimal solutions for multi objective problem based on natural selection, the process that drives biological evolution. The genetic algorithm repeatedly modifies a population of individual solutions.

At each step of iteration, the genetic algorithm selects individuals at random from the current population to be parents and uses them produce the children for the next generation. Over successive generations, the population gives an optimal solution. The GA can be used to solve a variety of optimization problems including problems in which the objective function is discontinuous, non-differentiable, stochastic, or highly nonlinear. Main components of GA are initialization, selection, crossover, mutation and termination as in [18-19].

4.1. Steps in GA

The steps that are to be followed for the placement of SVC, TCSC and UPFC in GA are:

Step 1: Create an initial population

Step 2: Run power flow program.

Step 3: Evaluate fitness value of all the individuals.

Step 4: Select a new population from the old population based on the fitness of the individuals as given by the evaluation function.

Step 5: Apply genetic operators (crossover and mutation) to members of the population to create new solutions.

Step 6: Evaluate the fitness value of new chromosomes and insert them into the population.

Step 7: If time is up, stop and return the best individual if not, go to step 4.

5. Results and Discussion

The proposed algorithm was tested on IEEE 14 bus and IEEE 57 bus systems as in [20-21] and the results were obtained. In which the optimal location and ratings of SVC, TCSC and UPFC were found and the objectives such as fuel cost of generation, voltage stability index and power losses were minimized using GA technique. The parameters used for this technique is shown in Table 1. This proves that the GA is more efficient than the conventional method.

Table 1.GA Parameters.

Population	20
Crossover fraction	0.8
Selection function	Stochastic uniform
Elite count	2
Crossover function	Scattered

5.1. IEEE 14 bus system

It contains 20 transmission lines. The test system consists of 5 generator buses (bus no.1,2,3,6 and 8), 9 load buses (bus no.4,5,7,9,10,11,12,13 and 14) and 20 transmission lines. The total system demand is 259 MW. Optimal location and rating of SVC, TCSC and UPFC have been found for IEEE 14 bus using GA technique and it is shown in Table 2. GA convergence characteristics of IEEE 14 bus system for SVC, TCSC and UPFC are shown in Figs. 4 - 6.

Table 2.Optimal location and rating of SVC, TCSC and UPFC for IEEE 14 bus using GA.

SVC		TCSC		UPFC
Location	**Rating**	**Location**	**Rating**	**Location**
Bus 4	0.1894	Line 9-14	23% of line reactance	Line 9-10

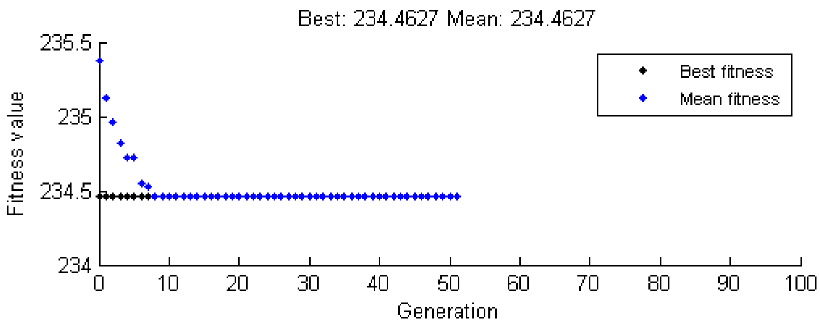

Fig. 4. GA convergence characteristics of IEEE 14 bus system for SVC.

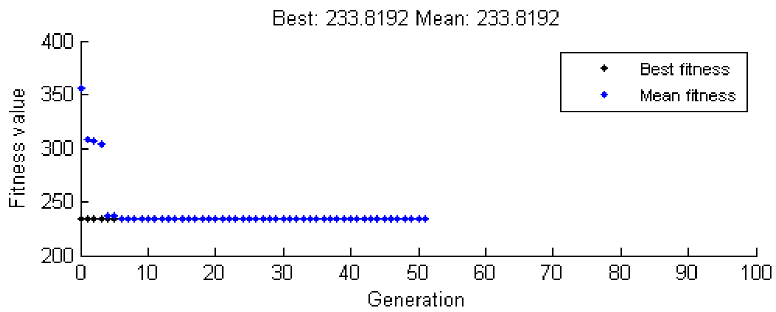

Fig. 5. GA convergence characteristics of IEEE 14 bus system for TCSC.

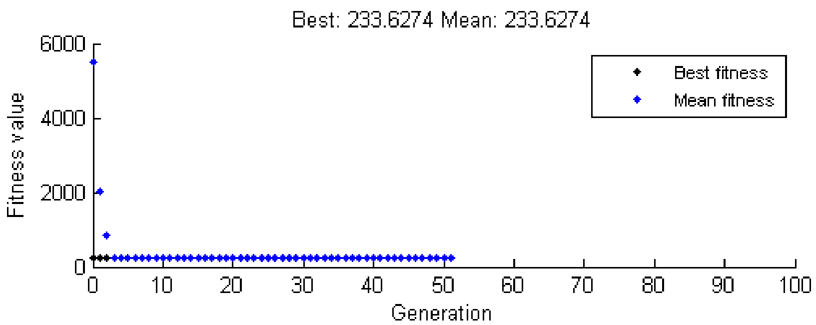

Fig. 6. GA convergence characteristics of IEEE 14 bus system for UPFC.

Bus 4 is identified as optimal location of SVC using GA and susceptance rating of SVC is 0.1894 p.u. Voltage profile is increased at all the buses and voltage stability index is decreased from 0.0783 to 0.0772, real power loss is reduced by 0.0946 MW and generator cost is reduced by 0.5611 $/Hour. Line 9-14 is identified as optimal location of TCSC and reactance rating of TCSC is 23% of line reactance. Voltage profile is increased at all the buses and voltage stability index is decreased from 0.0783 to 0.0732, real power loss is reduced by 2.0378 MW and generator cost is reduced by 0.2278 $/Hour. Line 9-10 is identified as optimal location of UPFC. Voltage profile is increased at all the buses and voltage stability index is decreased from 0.0783 to 0.0706, real power loss is reduced by 2.2348 MW and generator cost is reduced by 0.6343 $/Hour. Real power loss reduction with UPFC is more than SVC. Real power loss is reduced with TCSC is more than SVC. UPFC results are better than SVC and TCSC. Voltage profile of IEEE 14 bus system without FACTS device is compared with SVC, TCSC and UPFC and it is shown in Fig. 7.

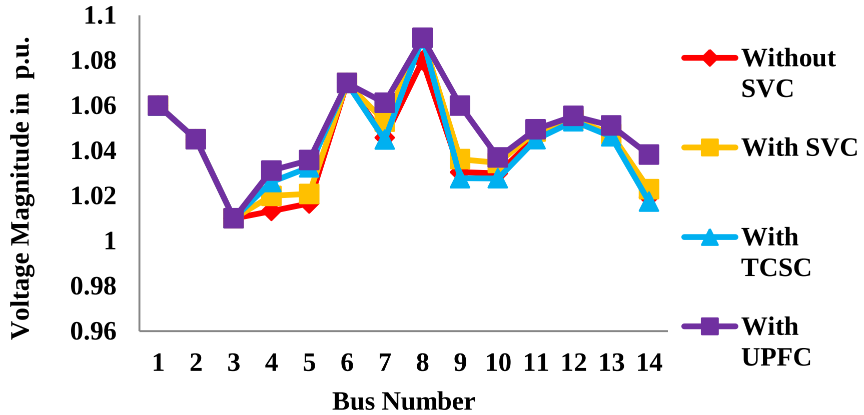

Fig. 7. Voltage profile of IEEE 14 bus system.

Similarly voltage stability index, real power loss, generator cost and total objective function of IEEE 14 bus system without FACTS device is compared with SVC, TCSC and UPFC and it is shown in Figs. 8-11.

Fig. 8. Comparison of voltage stability index of IEEE 14 bus system.

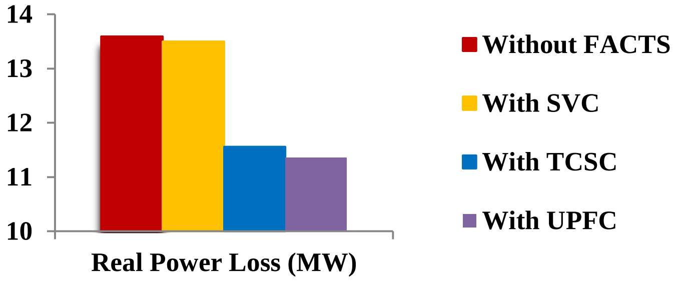

Fig. 9. Comparison of real power loss of IEEE 14 bus system.

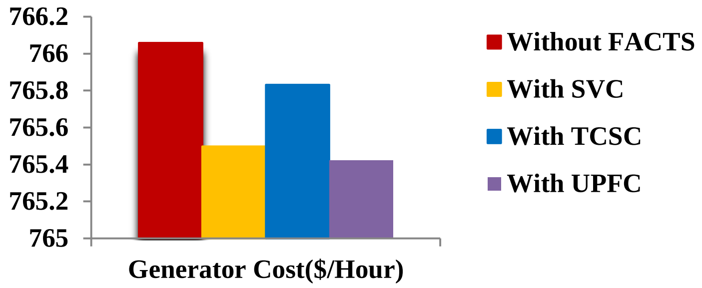

Fig. 10. Comparison of generator cost of IEEE 14 bus system.

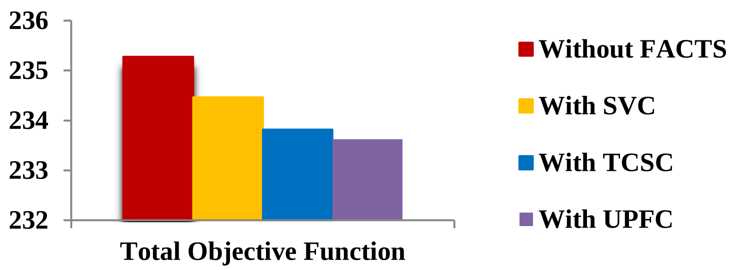

Fig. 11. Comparison of total objective function of IEEE 14 bus system.

5.2. IEEE 57 bus system

IEEE 57 bus system consists of 7 generator buses (bus no. 1,2,3,6,8,9,12) 50 load buses (bus no. 4, 5, 7, 10, 11, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57) and 80 transmission lines. Bus 1 is slack bus and the total system demand is 1195.8 MW and 319.4 MVAR. Optimal location and rating of SVC, TCSC and UPFC have been found for IEEE 57 bus using GA technique and it is shown in Table 3. GA convergence characteristics of IEEE 57 bus system for SVC, TCSC and UPFC are shown in Figs. 12-14.

Bus 38 is identified as optimal location of SVC using GA and susceptance rating of SVC is 0.008 p.u. Voltage profile is increased at all the buses and voltage stability index is decreased from 0.3218 to 0.2852, real power loss is reduced by 0.865 MW and generator cost is reduced by 2.9 $/Hour. Line 38-49 is identified as optimal location of TCSC and reactance rating of TCSC is 22% of line reactance. Voltage profile is increased at all the buses and voltage stability index is decreased from 0.3218 to 0.2155, real power loss is reduced by 10.4816 MW and generator cost is reduced by 24 $/Hour. Line 9-12 is identified as optimal location of UPFC. Voltage profile is increased at all the buses and voltage stability index is decreased from 0.3218 to 0.2098, real power loss is reduced by 11.3487 MW and generator cost is reduced by 24.7 $/Hour. Real power loss is reduced with UPFC is more than SVC. Real power loss is reduced with TCSC is more than SVC. UPFC gives better results than SVC and TCSC. Voltage profile of IEEE 57 bus system without FACTS device is compared with SVC, TCSC and UPFC and it is shown in Fig. 15.

Table 3. Optimal Location and Rating of SVC, TCSC and UPFCfor IEEE 57 Bus using GA.

SVC		TCSC		UPFC
Location	**Rating**	**Location**	**Rating**	**Location**
Bus 38	0.008	Line 38-49	22% of line reactance	Line 9-12

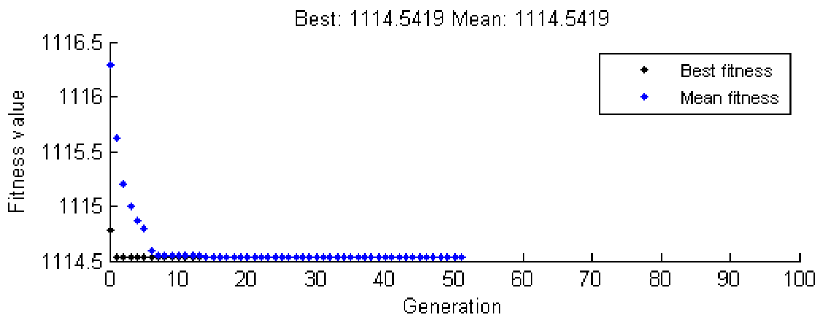

Fig. 12. GA convergence characteristics of IEEE 57 bus system for SVC.

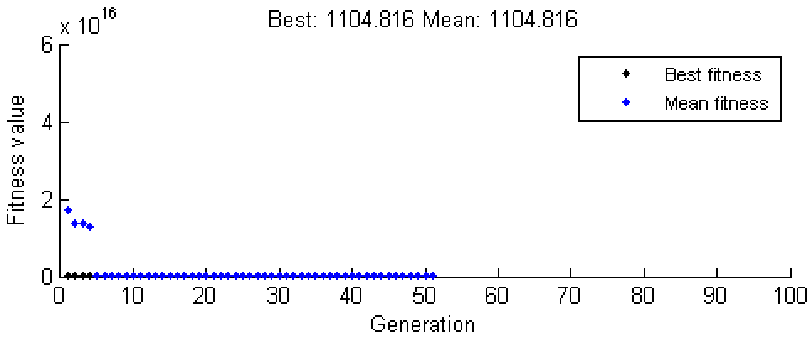

Fig. 13. GA convergence characteristics of IEEE 57 bus system for TCSC.

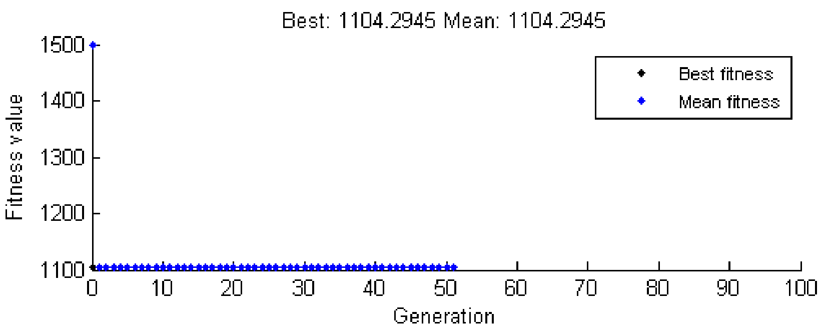

Fig. 14. GA convergence characteristics of IEEE 57 bus system for UPFC.

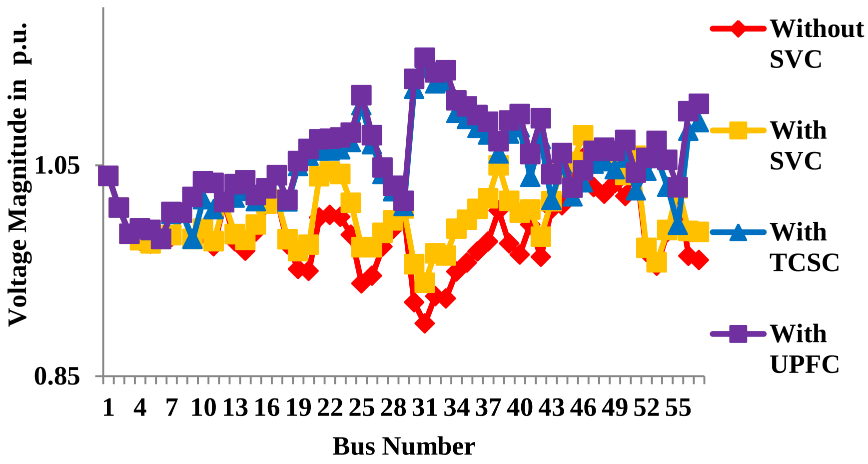

Fig. 15. Voltage profile of IEEE 57 bus system.

Similarly voltage stability index, real power loss, generator cost and total objective function of IEEE 57 bus system without FACTS device is compared with SVC, TCSC and UPFC and it is shown in Figs. 16-19.

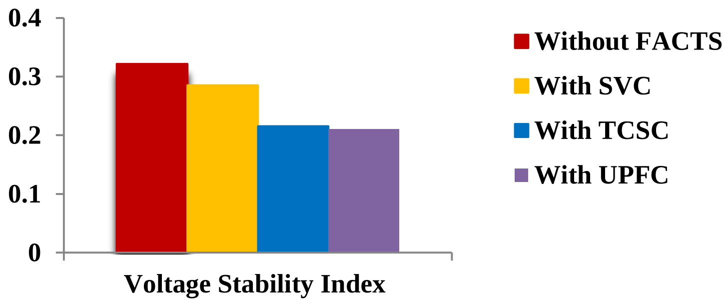

Fig. 16. Comparison of voltage stability index of IEEE 57 bus system.

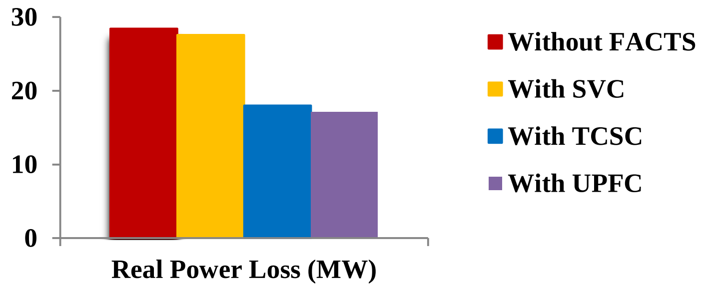

Fig. 17. Comparison of real power loss of IEEE 57 bus system.

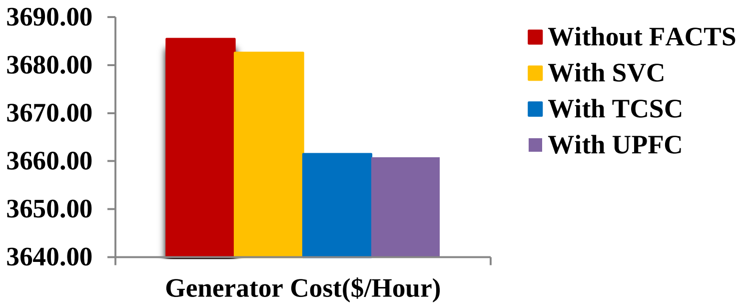

Fig. 18. Comparison of generator cost of IEEE 57 bus system.

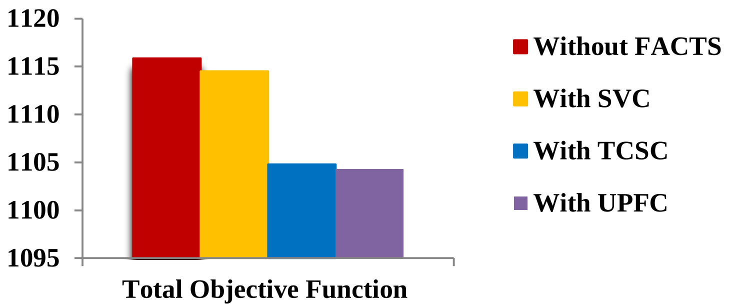

Fig. 19. Comparison of total objective function of IEEE 57 bus system.

6. Conclusion

This paper made an attempt to find the optimal location and size of SVC, TCSC and UPFC devices to avoid voltage instability and voltage collapse. Multi-objective optimization problem consists of multiple objectives such as minimization of voltage stability index, cost of generating unit and real power loss has been considered and GA is used to give optimization results. Simulations were performed on IEEE 14 bus and IEEE 57 bus systems. It is observed that the voltages stability margin is improved, voltage profile of the power system is increased, real power loss and cost of generating unit are also reduced by optimally locating SVC, TCSC and UPFC devices in the power system. Results of both power system with SVC, TCSC and UPFC devices and without FACTS devices are compared. UPFC improves voltage profile better than TCSC and UPFC reduces real power loss than SVC. UPFC gives better results than SVC and TCSC. Results of power system with SVC, TCSC and UPFC devices are better than that of normal system without FACTS devices.

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