Voltage and Real Power Loss Analysis Incorporating CE-SSSC with VS-SVC Combination through Fruit Fly Optimization

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Abstract: - This paper focuses an application of Fruit fly Optimization Algorithm based voltage stability enhancement and minimization of real power loss incorporating the combination of Series – Shunt flexible AC transmission system (FACTS) controllers named as Static Synchronous Series Compensator (SSSC) combined with Static Var Compensator (SVC). A new circuit element model of SSSC (CE-SSSC) with variable susceptance model of SVC (VS-SVC) is utilized to control the line power flows and bus voltage magnitudes respectively for real power loss minimization and voltage stability limit improvement. The line quality proximity index (LQP) is used to assess the voltage stability of a power system. The values of Voltage profile improvement, real power loss minimization and the location and size of FACTS devices were optimized Fruit fly Optimization Algorithm (FOA). The results are obtained from three power system test cases (IEEE 14 bus, IEEE 30 bus, IEEE 57 bus) and one practical case such as Indian Utility Neyveli Thermal Power Station (IU-NTPS) 23 bus system and compare with other leading evolutionary techniques such as Shuffled Frog Leaping Algorithm (SFLA), Differential Evolution (DE), Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) under three different cases such as normal loading, critical loading and single line outage conditions.

Key-Words: - Fruit Fly Optimization Algorithm, Voltage Stability, Static Var Compensator, Line Stability Index, FACTS Devices, Load Flow.

1 Introduction

Voltage stability is concerned with the ability of a power system to maintain acceptable voltage at all load buses in the system under normal conditions and after being subjected to a disturbance [1]. The recent day power systems are undergoing numerous changes and becoming more complex from operation, control and stability maintenance stand points when they meet ever-increasing load demand [2-3]. A system enters a state of voltage instability when a disturbance, increase in load demand, or change in system condition causes a progressive and uncontrollable decline in voltage. The main factor causing voltage instability is the inability of the power system to meet the demand for reactive power [4-5]. The authors [6-7] discuss methods to assess voltage stability of a power system to find possible ways to improve the voltage stability.

Abnormal voltages and voltage collapse pose a primary threat to power system stability, security and reliability. Moreover, with the fast development of restructuring, the problem of voltage stability has become a major concern in deregulated power systems. To maintain security of such systems, it is desirable to plan suitable measures to improve power system security and increase voltage stability margins [8-9]. Voltage instability is one of the phenomena which have resulted in major blackouts. Recently, several network blackouts have been related to voltage collapse [10]. The only way to counteract this problem is by reducing the reactive power load in the system or by adding new reactive power generation systems in the weakest points of the system, thereby, increasing the voltage at those points.

The Flexible AC Transmission System (FACTS) controllers are capable of supplying or absorbing of reactive power at faster rates [11-12]. The introduction of FACTS controllers are increasingly used to provide voltage and power flow controls [13-14]. Insertion of FACTS devices is found to be highly effective in preventing voltage instability and minimize the active or real power loss on transmission lines [15-16]. Series and shunt compensating devices are used to enhance the Static voltage stability margin and reduce the real power loss appreciably [17-19].

The generalized power injection model of SSSC needs modification of the Jacobian matrix and makes quiet complex in coding. In the SSSC control parameters, voltage magnitude and angle of the series converters are presented as independent variables and their values are found through the traditional load flow iterative process [20]. In this case, the size of the Jacobian matrix increases to incorporate the additional independent variables. The new model of the SSSC changes only the bus admittance matrix and consequently reduces the coding of load flow problem incorporating SSSC simple. The SSSC control parameters, voltage magnitude and angle of the series converters, are presented as independent variables and their values are found through the traditional load flow iterative process. In this case, the size of the Jacobian matrix increases to incorporate the additional independent variables. Hence a simple and easy to implement SSSC model based on the circuit elements is used in this work [21].

Voltage stability assessment with appropriate representations of FACTS devices are investigated and compared under base case of study [22-24]. One of the shortcomings of those methods only considered the normal state of the system [25-26]. The author [27] presented the different computational techniques for voltage stability assessment and control. However voltage collapses are mostly initiated by a disturbance like line outages. Voltage stability limit improvement needs to be addressed during network contingencies. So to locate FACTS devices, consideration of contingency conditions is more important than consideration of normal state of system and some approaches are proposed to locate of FACTS devices with considerations of contingencies too [28-29].

Line stability indices provide important information about the proximity of the system to voltage instability and can be used to identify the weakest bus as well as the critical line with respect to the bus of the system [30]. Different types of line stability indices are proposed to evaluate the proximity of the system to voltage instability [31-33] The Line Quality Proximity index is used in this work for stability assessment [34-35]. The author [36-38] expresses to maximize the voltage stability improvement and minimize the real power loss through two recent evolutionary techniques. From the family of bio inspired computation, Fruit fly Optimization Algorithm (FOA) is used to solve the problem of real power loss minimization and Voltage stability maximization of the system. It is a new bio inspired optimization algorithm based on fruit fly's foraging behavior and most researchers has used this algorithm for many optimization problems [39-40]. The visual senses of fruit flies are superior to that of other species. They can successfully pick up various odors floating in the air with their olfactory organ; some can even smell food sources 40 kilometers away. Then, they would fly to the food. They may also spot with their sharp vision food or a place where their companions gather.

Because of higher cost of the FACTS devices, the installation is not recommended to all possible line outages. Hence line outage contingency screening and ranking carried out to identify the most critical line during whose outage FACTS controllers can be positioned and system can be operated under stable condition [41-43]. The key objective of this work is to obtain the results from IEEE 14, 30, 57 bus test cases and IU-NTPS 23 bus practical cases through FOA with combination of SSSC-SVC FACTS controller and compare the results with other important evolutionary techniques under three different cases such as normal loading, critical loading and single line outage conditions.

2 Static Model of CE-SSSC

The SSSC can be operated without an external energy source as reactive power source and is fully controllable independent of transmission line current for the purpose of increasing or decreasing the overall reactive voltage drop across the transmission line and thereby controlling the electric power flow. The widely used power injection model of SSSC requires modification of the Jacobian matrix and makes the Newton-Raphson load flow (NRLF) coding more complex. A new circuit elements based model of SSSC is utilized to control the line power flows and bus voltage magnitudes for voltage stability limit improvement. The new model of the SSSC changes only the bus admittance matrix and consequently reduces the coding of load flow problem incorporating SSSC simple. This converter performs the main function of injecting a controllable series voltage. The basic configuration of SSSC is depicted in Figure 1. The model of SSSC is also shown in Figure 2.

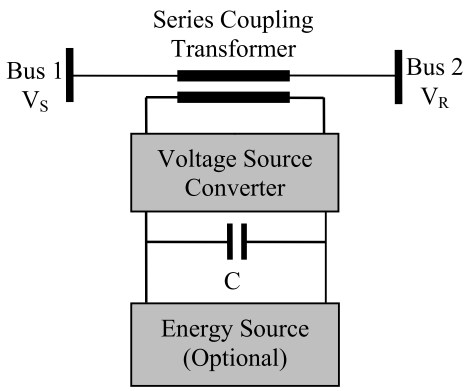


Fig. 1 SSSC Configuration

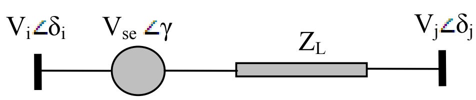


Fig. 2 Circuit Model of SSSC

The real and reactive powers exchanged with the line by the series voltage inserted by SSSC are modelled as a negative resistance and reactance connected in parallel. The negative resistance represents injection of real power and the reactance may be either capacitive or inductive depending on whether reactive power is delivered or absorbed. The complex power exchanged by the series converter with the line is expressed as

$$S_e = V_{se} I \quad (1)$$

where V_{se} is the complex voltage injected by the converter and I the current through the line given by

$$I = \frac{V_i\angle\delta_i + V_{se}\angle\gamma - V_j\angle\delta_j}{Z_L} \quad (2)$$

The active and reactive powers exchanged with the line are modeled as resistance and reactance associated as represented by

$$R = \frac{V_{se}^2}{P_{se}} \quad (3)$$

$$X = \frac{V_{se}^2}{Q_{se}} \quad (4)$$

The elements R and X can be calculated by directly using the following equations.

$$R = \frac{V_{se} Z_L}{V_i \sin(\delta_i - \delta_j - \gamma) + V_j \sin\gamma} \quad (5)$$

$$X = \frac{V_{se} Z_L}{V_i \cos(\delta_i - \delta_j - \gamma) - V_j \cos\gamma + V_{se}} \quad (6)$$

The resistance R and the reactance X representing the effect of series voltage are transformed into their equivalent series combination. This makes the line simple with only series connected elements of the line (ZL) and the RSSSC and XSSSC denoting the resistance and reactance of SSSC.

$$R_{SSSC} = \frac{RX^2}{R^2 + X^2} \quad (7)$$

$$X_{SSSC} = \frac{XR^2}{R^2 + X^2} \quad (8)$$

3 Static Model of VS-SVC

A variable susceptance B_{SVC} represents the fundamental frequency equivalent susceptance of all shunt modules making up the SVC. This model is an improved version of SVC models. Figure 3 shows the variable susceptance model of SVC which is used to derive its nonlinear power equations and the linearised equations required by Newton's load flow method.

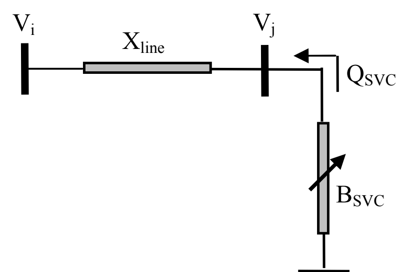


Fig. 3 Variable Susceptance model of SVC

In general, the transfer admittance equation for the variable shunt compensator is

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

The reactive power of SVC is

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

In SVC susceptance model the total susceptance B_{SVC} is taken to be the state variable, therefore the linearised equation of the SVC is given by

$$\begin{bmatrix} \Delta Pj \\ \Delta Qj \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & \theta_j \end{bmatrix} \begin{bmatrix} \Delta\theta j \\ \Delta Bsvc/Bsvc \end{bmatrix} \quad (11)$$

where ΔP_j, ΔQ_j, $\Delta\theta_j$ are the change in real, reactive power and voltage angle at j^{th} bus.

At the end of iteration i the variable shunt susceptance B_{SVC} is updated according to

$$B_{SVC}^{(i)} = B_{SVC}^{(i-1)} + (\Delta B_{SVC}/B_{SVC})^{(i)} B_{SVC}^{(i-1)} \quad (12)$$

This changing susceptance value represents the total SVC susceptance which is necessary to maintain the nodal voltage magnitude at the specified value (1.0 p.u. in this paper).

4 Line Quality Proximity Index

Voltage stability can be assessed in a system by calculating the line based voltage stability index. The LQP index based on a power transmission concept is used in this paper. The value of line index shows the voltage stability of the system. The value close to unity indicates that the respective line is close to its stability limit and value much close to zero indicates light load in the line. The formulation begins with the power equation in a power system. Figure 5 illustrates a single line of a power transmission concept.

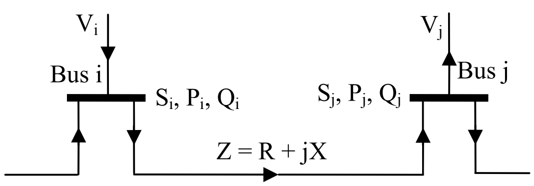


Fig. 5 Single line concept of power transmission

The power equation can be derived as

$$P_i = \sqrt{\frac{V_i^2}{X}\left(Q_i - Q_j\right) - Q_i^2} \quad (13)$$

The line stability factor is obtained by setting the discriminant of the reactive power roots at bus 1 to be greater than or equal to zero, thus defining the line stability factor, LQP as,

$$LQP = 4\left(\frac{X}{V_i^2}\right)\left(\frac{X}{V_i^2} P_i^2 + Q_j\right) \quad (14)$$

5 Problem Formulation

The objective function of this work is to find the optimal rating and location of FACTS devices combination which minimizes the real power loss, minimization of voltage deviation and maximizes the voltage stability limit. Hence, the objective function can be expressed as:

$$F = \min\{P_L + wVD + (1-w)LQP\} \quad (16)$$

where w is the weighing factor for voltage deviation and LQP index and is set to 10.

5.1 Minimization of Real Power Loss (P_L)

The total real power of the system can be calculated as follows

$$P_{loss} = \sum_{k=1}^{N_L} G_k[V_i^2 + V_j^2 - 2|V_i||V_j|\cos(\delta_i - \delta_j)] \quad (17)$$

where , N_L is the total number of lines in the system; G_k is the conductance of the line 'k'; V_i and V_j are the magnitudes of the sending end and receiving end voltages of the line; δ_i and δ_j are angles of the end voltages.

5.2 Minimization of Load Bus Voltage Deviation (VD)

Bus voltage magnitude should be maintained within the allowable range to ensure quality service. Voltage profile is improved by minimizing the deviation of the load bus voltage from the reference value (it is taken as 1.0 p.u. in this work).

$$VD = \sum_{k=1}^{N_{PQ}} |(V_i - V_{ref})| \quad (18)$$

where V_i is the voltage at i^{th} bus and V_{ref} is the reference voltage.

5.3 Minimization of Line Quality Proximity Index (LQP)

Voltage stability limit of a power system is increased by minimizing voltage stability index value. The indicator takes values between 0 (no-load) and 1 (full load). The line based stability index (LQP) is given as

$$LQP = \sum_{j=1}^{N_L} LQP_j \quad (19)$$

5.4 Constraints

The minimization problem is subject to the following equality and inequality constraints.

Equality constraints

Load Flow Constraints:

$$P_{Gi} - P_{Di} - \sum_{j=1}^{N_B} V_i V_j Y_{ij} \cos\left(\delta_{ij} + \gamma_j - \gamma_i\right) = 0 \quad (20)$$

$$Q_{Gi} - Q_{Di} - \sum_{j=1}^{N_B} V_i V_j Y_{ij} \sin\left(\delta_{ij} + \gamma_j - \gamma_i\right) = 0 \quad (21)$$

where, P_{Gi}, Q_{Gi} are the active and reactive power of i_{th} generator, P_{Di} , Q_{Di} the active and reactive power of i_{th} load bus.

Inequality constraints

Reactive Power Generation Limit of SVCs:

By choosing small sized compensator, capital cost is involved can be minimum. The size limit of SVC has been taken from minimum of 5 MVAR to maximum of 20 MVAR.

$$Q_{SVCi}^{min} \leq Q_{SVCi} \leq Q_{SVCi}^{max}; i \in N_{SVC} \quad (22)$$

where, Q_{SVCi}^{min}, Q_{SVCi}^{max} are the minimum and maximum VAR injection limits of i_{th} shunt capacitor.

Reactance Limits of TCSCs:

$$-0.8X_{ij} \leq X_{TCSC\,k} \leq 0.2X_{ij}; k \in N_{TCSC} \quad (23)$$

where, $X_{TCSC\,k}$ is the reactance of k^{th} TCSC and N_{TCSC} is the number of TCSC.

Voltage Constraints:

The acceptable voltage limits in all load buses are taken from 0.95 p.u to 1.05 p.u. to avoid voltage instability.

$$V_i^{min} \leq V_i \leq V_i^{max}; i \in N_B \quad (24)$$

where, V_i^{min}, V_i^{max} are the minimum and maximum value voltage of bus 'i'.

Transmission line flow limit:

$$S_i \leq S_i^{max}; i \in N_l \quad (25)$$

where, S_i is the apparent power flow of i_{th} branch and S_i^{max} is the maximum apparent power flow limit of i_{th} branch.

6 Fruit Fly Optimization Algorithm

6.1 Over view

In recent years researchers are much attracted by foraging intelligence of animals. Global optimization algorithms are developed by mimicking the food searching behaviour of animals. These algorithms are found to be efficient in most of the engineering optimization problem. Taiwanese scholar Pan introduced one such bio inspired algorithm, the fruit fly algorithm [39]. It is a new bio inspired optimization algorithm based on fruit fly's foraging behaviour and most researchers has used this algorithm for many optimization problems. The visual senses of fruit flies are superior to that of other species. They can successfully pick up various odours floating in the air with their olfactory organ; some can even smell food sources 40 kilometres away. Then, they would fly to the food. They may also spot with their sharp vision food or a place where their companions gather. The major advantages of this algorithm is, it is with less number of parameters and easy for implementation for any engineering problem. Fruit fly's foraging characteristics have been summarized and programmed into the following steps.

Step1: Randomly generate a fruit fly swarm's initial position

$$\text{Init X axis; Init Y axis} \quad (26)$$

Step2: Randomly assign every fruit fly a direction and distance for their movement to look for food with their olfactory organ.

$$X_i = X_{axis} + Random\ Value \quad (27)$$

$$Y_i = X_{axis} + Random\ Value \quad (28)$$

Since food's position is unknown, the distance ($Dist_i$) to the origin is estimated first, and the judged value of smell concentration (S_i), which is the inverse of distance, is then calculated.

$$Dist_i = \sqrt{\left(X_i^2 + Y_i^2\right)}; \quad S_i = 1/Dist_i \quad (29)$$

Step 3: Substitute the judged values of smell concentration (S_i) into the smell concentration judge function (also called fitness function) to get the smell concentrations ($Smell_i$) of at positions of each and every fruit flies

$$Smell_i = Function(S_i) \quad (30)$$

Step 4: Identify the fruit fly whose position has the best smell concentration (maximum/minimum value)

$$[\text{bestSmellbestIndex}] = \max(\text{Smell}) \quad (31)$$

Step 5: Keep the best smell concentration value and x, y coordinate; the fruit fly swarm will see the place and fly towards the position.

$$\text{Smellbest} = \text{bestSmell} \quad (32)$$

$$\text{X axis} = \text{X(bestIndex)} \quad (33)$$

$$\text{Y axis} = \text{Y(bestIndex)} \quad (34)$$

Step 6: Enter iterative optimization, repeat steps 2-5 and judge whether the smell concentration is higher than that in the previous iteration; if so, carry out step 6.

6.2 Implementation

Step 1: Initialize the algorithm parameters like population size, maximum number of generations and global best.

Step 2: Each fruit fly is a vector of the control variables. i.e.. $X_i = [Q_{SVCi}, X_{TCSCi}, R_i + jX_i]$ *NP* number o agents are generated by respecting the limits of control parameters.

Step 3: Calculate the smell (fitness function values) of all flies by running the NR load flow.

Step 4: Sort the flies in the descending order of their fitness and determine the best fly that has more smell.

Step 5: Generate new flies using the information of the global best fly in the previous iteration. The global best is updated from iteration to iteration.

Step 6: Repeat step 2 to step 5 until stopping criteria has been achieved. The optimal values of firefly parameters are given in Table 1.

Table 1: Optimal values of FOA parameters

Parameters	Optimal Values
Number of Fruit flies	30
Maximum Generation	200
Random Variable	0.4

7 Results and Discussion

The proposed work is coded in MATLAB 7.6 platform using 2.8 GHz Intel Core 2 Duo processor based PC. The method is tested with IEEE 14, 30, 57 test cases and Indian Utility Neyveli Thermal Power Station (IU-NTPS) 23 bus practical system.

The line data and bus data are taken from the standard power system test case archive. The 14 bus system has 5 generator buses, 9 load buses and 20 transmission lines. The 30 bus system has 6 generator buses, 24 load buses and 41 transmission lines. The 57 bus system has 7 generator buses, 50 load buses and 80 transmission lines. The IU-NTPS 23 bus system has 4 generator buses, 19 load buses and 22 transmission lines. System data and results are based on 100 MVA and bus no 1 is the reference bus. In order to verify the presented models and illustrate the impacts of series-shunt FACTS controller named as SSSC-SVC combination study under three different operating conditions are considered as mentioned below.

Case 1: The system with normal load in all the load buses is considered as normal condition and the Newton-Raphson load flow is carried out with loading factor value equal to 1.

Case 2: The system with 50 % increased load in all the load buses is considered as a critical condition. Loading of the system went beyond this level, results in poor voltage profile in the load buses and unacceptable real power loss level.

Case 3: Contingency is imposed by considering the most critical line outage in the system. This is the most suitable condition for voltage stability analysis of a power system as voltage stability is usually triggered by line outages

Newton–Raphson program is repeatedly run with the absence and presence FACTS devices individually. The voltage stability limit improvement is assessed by the value of LQP index.

The voltage stability index values of top five stressed lines under all cases with pre insertion and post insertion of FACTS devices are shown in Table 2. It is evident from the table that LQP values of the stressed lines are reduced after placement of FACTS devices in the system.

Table 2: Voltage stability index values of most stressed lines

(a) For IEEE 14 bus system

Cases	Line No.	Pre insertion of FACTS	Post insertion of FACTS				
			FOA	SFLA	DE	PSO	GA
Case 1	14	0.1122	0.0757	0.0818	0.0807	0.0829	0.0833
	20	0.0776	0.0351	0.0537	0.0544	0.0617	0.0688
	1	0.0688	0.0517	0.0511	0.0491	0.0519	0.0537
	17	0.0593	0.0107	0.0388	0.0324	0.0503	0.0507
	2	0.0591	0.0497	0.0314	0.0443	0.0491	0.0518
Case 2	10	0.2580	0.1164	0.1722	0.1414	0.1704	0.1919
	14	0.1815	0.0858	0.0991	0.1012	0.1124	0.1219
	20	0.1494	0.0883	0.0941	0.1109	0.1156	0.1204
	9	0.1393	0.0607	0.0994	0.1003	0.1067	0.1104
	1	0.0799	0.0525	0.0604	0.0597	0.0661	0.0698
Case 3	10	0.1904	0.0645	0.0941	0.1022	0.1058	0.1204
	14	0.1642	0.0109	0.0507	0.0521	0.0614	0.0652
	15	0.1160	0.0787	0.0802	0.0114	0.0124	0.0131
	6	0.0914	0.0207	0.0241	0.0337	0.0384	0.0380
	20	0.0869	0.0314	0.0320	0.0417	0.0501	0.0626

(b) For IEEE 30 bus system

Cases	Line No.	Pre insertion of FACTS	Post insertion of FACTS				
			FOA	SFLA	DE	PSO	GA
Case 1	12	0.3691	0.2969	0.3687	0.3700	0.3717	0.3710
	5	0.1284	0.0996	0.1264	0.0987	0.1051	0.1205
	13	0.1226	0.1141	0.0114	0.1169	0.1174	0.1181
	1	0.0797	0.0328	0.0228	0.0329	0.0618	0.0792
	15	0.0749	0.0667	0.0748	0.0752	0.0749	0.0724
Case 2	12	0.3899	0.2411	0.3877	0.3874	0.3816	0.3827
	5	0.3596	0.2721	0.3310	0.0793	0.2128	0.3109
	13	0.2549	0.1914	0.2355	0.2351	0.2493	0.2502
	16	0.1687	0.1212	0.1735	0.1767	0.1669	0.1691
	15	0.1255	0.0969	0.1245	0.1244	0.1253	0.1245
Case 3	12	0.3851	0.2692	0.3864	0.3686	0.3694	0.3711
	5	0.2198	0.1814	0.1824	0.1896	0.1920	0.1957
	13	0.1732	0.1418	0.1766	0.1152	0.1466	0.1499
	16	0.0836	0.0762	0.0855	0.0475	0.0612	0.0825
	1	0.0786	0.0652	0.0810	0.0568	0.0614	0.0630

(c) For IEEE 57 bus system

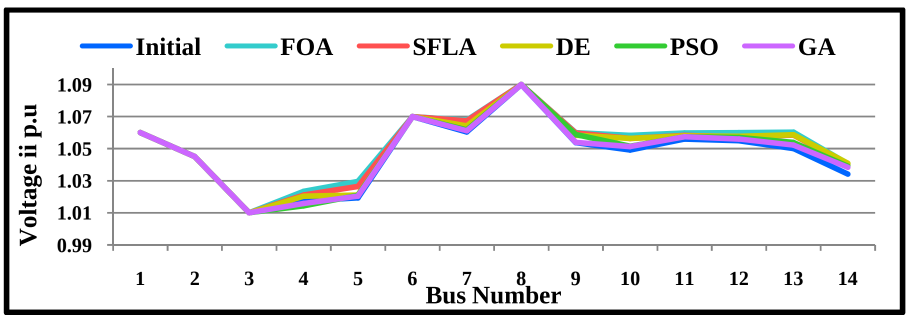
Cases	Line No.	Pre insertion of FACTS	Post insertion of FACTS				
			FOA	SFLA	DE	PSO	GA
Case 1	11	0.8896	0.2212	0.3025	0.3425	0.5002	0.5056
	2	0.5190	0.1298	0.0694	0.1024	0.1136	0.1066
	23	0.4607	0.1345	0.1757	0.2057	0.2123	0.2221
	7	0.2915	0.0969	0.0110	0.0110	0.0217	0.0221
	5	0.2601	0.1169	0.1402	0.1602	0.1885	0.2069
Case 2	11	0.8898	0.1687	0.2714	0.3214	0.4124	0.5689
	2	0.6032	0.0968	0.1017	0.1227	0.1337	0.3367
	23	0.5222	0.1444	0.1005	0.1405	0.2015	0.1845
	7	0.2957	0.1425	0.0454	0.0955	0.1098	0.1967
	5	0.2663	0.1218	0.1647	0.1891	0.2021	0.2051
Case 3	11	0.8851	0.1122	0.2911	0.3311	0.5005	0.5333
	2	0.5240	0.1776	0.2625	0.3067	0.3111	0.3023
	23	0.4259	0.0996	0.1075	0.1472	0.3217	0.3111
	7	0.2454	0.0244	0.0055	0.0023	0.1222	0.2205
	29	0.2241	0.1218	0.0458	0.0458	0.1621	0.1968

(d) For IU-NTPS 23 bus system

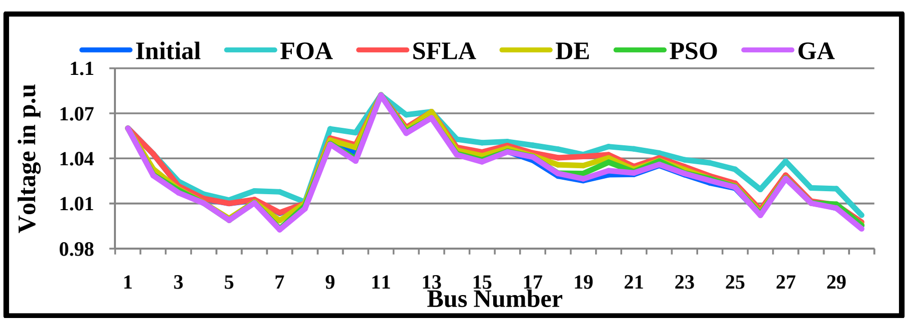
Cases	Line No.	Pre insertion of FACTS	Post insertion of FACTS				
			FOA	SFLA	DE	PSO	GA
Case 1	11	0.8663	0.2925	0.3058	0.4112	0.5419	0.6031
	10	0.5459	0.1033	0.1063	0.1264	0.2121	0.3112
	18	0.3991	0.0997	0.0936	0.0915	0.1612	0.2012
	5	0.1963	0.0885	0.0967	0.1051	0.1275	0.1652
	4	0.1420	0.0529	0.0302	0.0328	0.1056	0.1156
Case 2	11	0.9112	0.1214	0.1825	0.2054	0.2085	0.2110
	10	0.7253	0.1122	0.1030	0.1059	0.1245	0.1353
	18	0.5841	0.1007	0.1717	0.1919	0.2048	0.2036
	5	0.2258	0.0421	0.0922	0.0985	0.1212	0.1369
	2	0.2305	0.1006	0.1084	0.1005	0.1255	0.1256
Case 3	11	0.8214	0.1211	0.1805	0.2013	0.2132	0.2200
	10	0.6542	0.0963	0.0962	0.0936	0.1251	0.1018
	18	0.5127	0.0925	0.0909	0.0933	0.1001	0.1021
	5	0.2054	0.1414	0.0903	0.0958	0.1167	0.1167
	2	0.1969	0.0992	0.0915	0.1001	0.1085	0.1089

Table 3: Contingency ranking

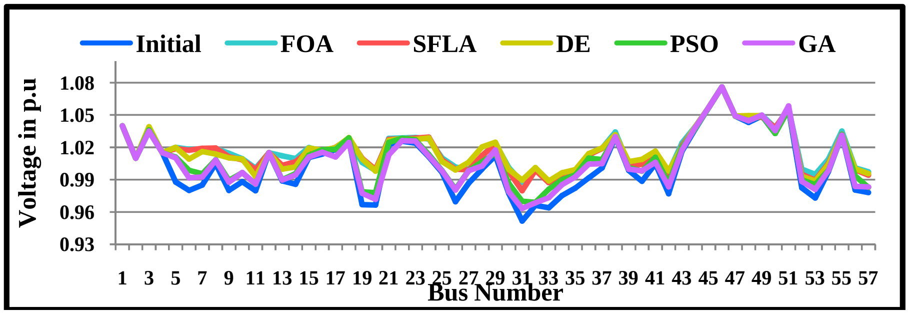
Rank	IEEE 14 Bus System		IEEE 30 Bus System		IEEE 57 Bus System		IU-NTPS 23 Bus System	
	Line Number	LQP Values	Line Number	LQP Values	Line Number	LQP Values	Line Number	LQP Values
1	1	0.5795	5	0.9495	11	0.8531	3	0.6872
2	3	0.3826	9	0.6050	23	0.8007	2	0.6778
3	10	0.3449	2	0.4993	7	0.6847	10	0.4549
4	2	0.3157	4	0.4968	22	0.2829	12	0.2287
5	15	0.1984	7	0.4693	2	0.2082	16	0.2164



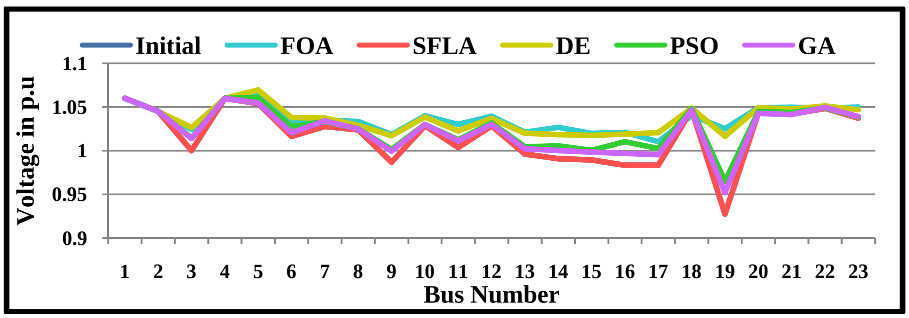
(i) For IEEE 14 bus system



(ii) For IEEE 30 bus system

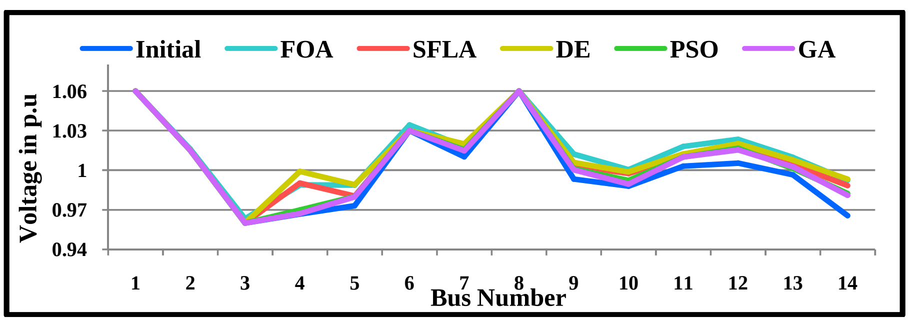


(iii) For IEEE 57 bus system

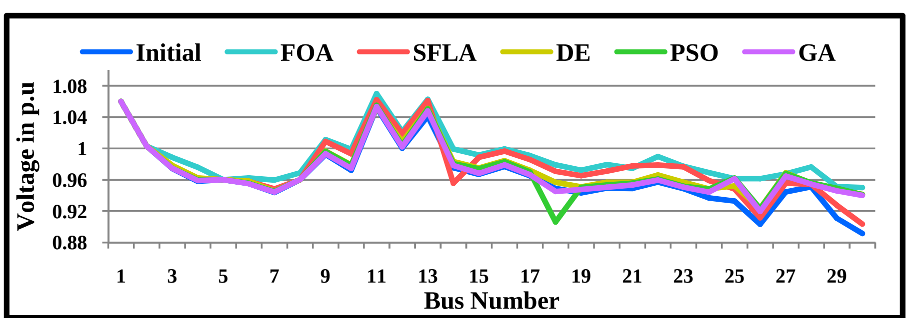


(iv) For IU-NTPS 23 bus system

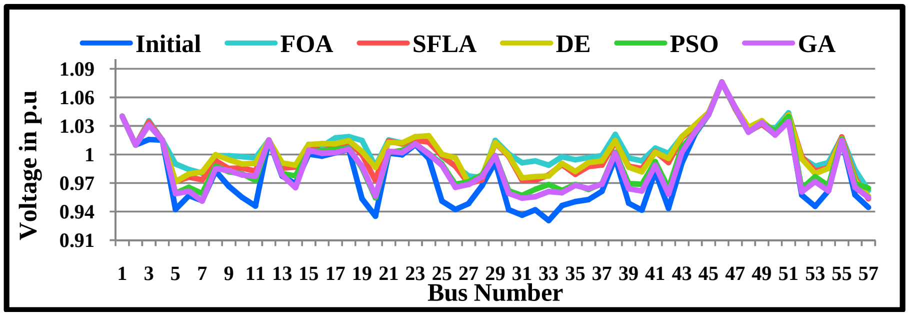
Fig. 5(a) Voltage profile values comparison under case 1



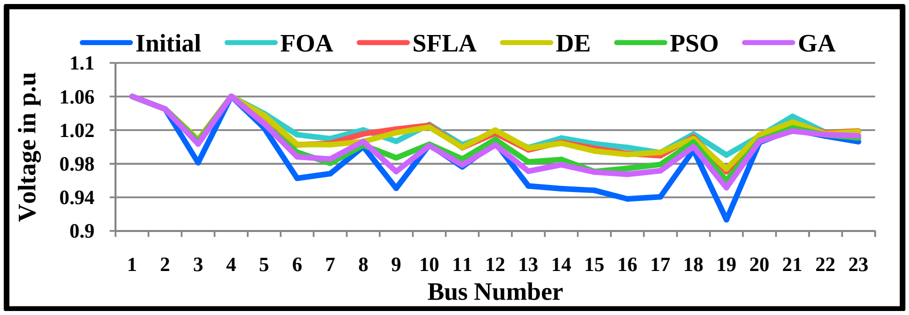
(i) For IEEE 14 bus system



(ii) For IEEE 30 bus system

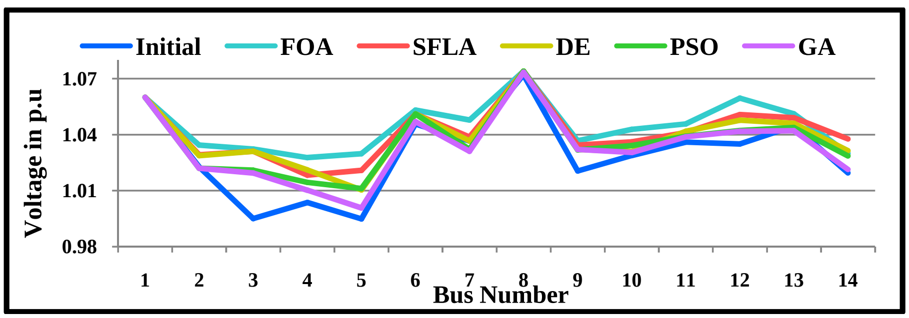


(iii) For IEEE 57 bus system

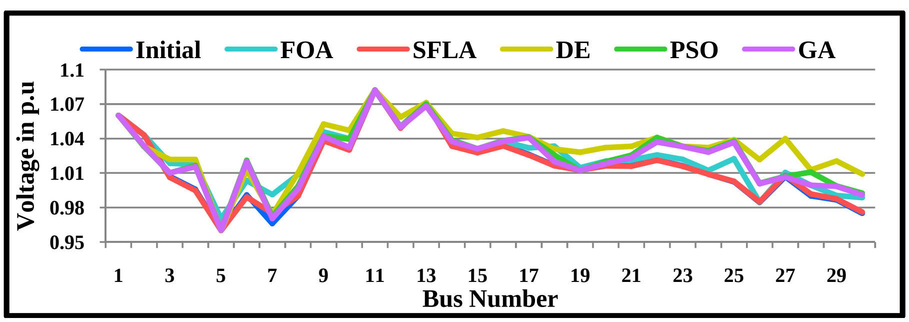


(iv) For IU-NTPS 23 bus system

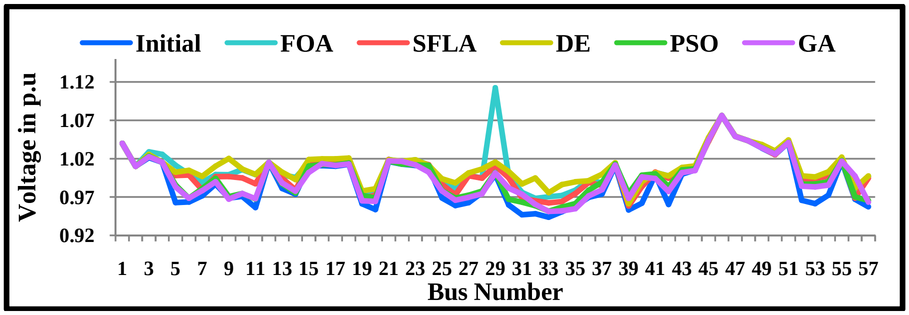
Fig. 5(b) Voltage profile values comparison under case 2



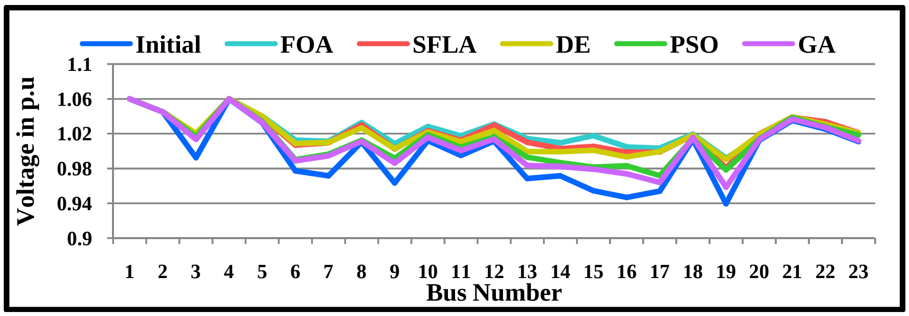
(i) For IEEE 14 bus system



(ii) For IEEE 30 bus system



(iii) For IEEE 57 bus system



(iv) For IU-NTPS 23 bus system

Fig. 5(c) Voltage profile values comparison under case 3

The line outage is ranked according to the severity and the severity is taken on the basis of the line quality proximity index values and such values are arranged in descending order. The maximum value of index indicates most critical line for outage. Line outage contingency screening and ranking is carried out on the test systems and the results are shown in Table 3.

It is clear from the above table that outage of line number 1 and 5 are the most critical line outages of IEEE 14 and IEEE 30 bus systems respectively. Similarly outage of line number 11 and 3 are the most critical line outages of IEEE 57 and IU-NTPS 23 bus systems respectively. This situation is considered for voltage stability improvement. Outage of other lines has not much impact on the system and therefore they are not given importance.

Load flow is run on the system with the lines are outaged. Outage of these lines results in large real power loss and voltage profile reduction in most of the load buses. The system is under stressed conditions and needs to be relieved by some means. Installation of FACTS devices at suitable locations can relive the system much from stressed conditions (reduced line losses). FACTS devices help the system to maintain acceptable voltage profile in the load buses. Under normal operating conditions most of the bus voltage magnitudes are within the normal value. During critical and contingency conditions voltage magnitude of remote load buses are below 0.95 (lower bound of allowable value). These bus voltages are improved after the FACTS devices are installed. Voltage profile comparisons under all cases are depicted separately in Figure 5.

It is obvious from the figure that voltage profile comparison of the system is improved better with the proposed method. The comparison of average value of load bus voltage also proves the enhancing behavior of voltage stability limit incorporating combination of FACTS devices of all cases shown in Table 4. Table 5 exposes the comparison of minimum and maximum load bus voltages both in the absence and presence of FACTS devices under all cases.

In real power loss minimization point of view, through insertion of FACTS devices, the real power loss under case 1 is decreased by 2.777 and 3.498 MW respectively for IEEE 14 and 30 bus systems. Similarly the real power loss is decreased by 7.549 and 4.488 MW respectively for IEEE 57 and IU-NTPS 23 bus systems. In case 2, the reduction in real power loss rate is 7.334 and 2.762 MW respectively for IEEE 14 and 30 bus systems. In IEEE 57 and IU-NTPS 23 bus systems the reduction is 11.766 and 8.824 MW respectively.

Table 4: Average load Bus voltage values in p.u

(a) For IEEE 14 bus system

Cases	Pre Insertion of FACTS	Post insertion of FACTS				
		FOA	SFLA	DE	PSO	GA
Case 1	1.0438	1.0510	1.0494	1.0483	1.0460	1.0451
Case 2	0.9890	1.0057	1.0013	1.0051	0.9965	0.9956
Case 3	1.0243	1.0412	1.0363	1.0331	1.0308	1.0276

(b) For IEEE 30 bus system

Cases	Pre Insertion of FACTS	Post insertion of FACTS				
		FOA	SFLA	DE	PSO	GA
Case 1	1.0262	1.0374	1.0306	1.0283	1.0265	1.0253
Case 2	0.9520	0.9795	0.9664	0.9635	0.9602	0.9596
Case 3	1.0106	1.0185	1.0108	1.0306	1.0222	1.0204

(c) For IEEE 57 bus system

Cases	Pre Insertion of FACTS	Post insertion of FACTS				
		FOA	SFLA	DE	PSO	GA
Case 1	1.0029	1.0172	1.0159	1.0166	1.0090	1.0070
Case 2	0.9781	1.0057	0.9998	1.0021	0.9902	0.9878
Case 3	0.9878	1.0060	1.0002	1.0071	0.9952	0.9941

(a) For IU-NTPS 23 bus system

Cases	Pre Insertion of FACTS	Post insertion of FACTS				
		FOA	SFLA	DE	PSO	GA
Case 1	1.0135	1.0346	1.0135	1.0338	1.0228	1.0193
Case 2	0.9775	1.0122	1.0084	1.0080	0.9947	0.9907
Case 3	0.9897	1.0183	1.0147	1.0133	1.0037	0.9993

Table 5: Minimum Maximum Load Bus Voltage Values in p.u

(a) For IEEE 14 bus system (Minimum)

Cases	V_{MIN}						
	Bus No.	Pre insertion of FACTS	Post insertion of FACTS				
			FOA	SFLA	DE	PSO	GA
Case 1	4	1.0173	1.0233	1.0211	1.0203	1.0143	1.0158
Case 2	14	0.9656	0.9887	0.9804	0.9890	0.9699	0.9672
Case 3	5	0.9948	1.0277	1.0183	1.0104	1.0111	1.0007

(b) For IEEE 14 bus system (Maximum)

Cases	V_{MAX}						
	Bus No.	Pre insertion of FACTS	Post insertion of FACTS				
			FOA	SFLA	DE	PSO	GA
Case 1	7	1.0604	1.0677	1.0673	1.0642	1.0617	1.0612
Case 2	7	1.0101	1.0234	1.0194	1.0202	1.0166	1.0154
Case 3	13	1.0446	1.0596	1.0507	1.0477	1.0438	1.0421

(c) For IEEE 30 bus system (Minimum)

Cases	V_{MIN}						
	Bus No.	Pre insertion of FACTS	Post insertion of FACTS				
			FOA	SFLA	DE	PSO	GA
Case 1	30	0.9953	1.0022	0.9976	0.9959	0.9932	0.9925
Case 2	30	0.8915	0.9501	0.9035	0.9236	0.9061	0.9196
Case 3	7	0.9661	0.9847	0.9750	0.9738	0.9721	0.9704

(d) For IEEE 30 bus system (Maximum)

Cases	V_{MAX}						
	Bus No.	Pre insertion of FACTS	Post insertion of FACTS				
			FOA	SFLA	DE	PSO	GA
Case 1	12	1.0576	1.0690	1.0606	1.0589	1.0577	1.0567
Case 2	12	1.0004	1.0214	1.0186	1.0083	1.0037	1.0021
Case 3	12	1.0495	1.0503	1.0490	1.0586	1.0502	1.0499

(e) For IEEE 57 bus system (Minimum)

Cases	V_{MIN}						
	Bus No.	Pre insertion of FACTS	Post insertion of FACTS				
			FOA	SFLA	DE	PSO	GA
Case 1	31	0.9516	0.9875	0.9798	0.9888	0.9690	0.9634
Case 2	33	0.9307	0.9622	0.9534	0.9564	0.9546	0.9511
Case 3	33	0.9437	0.9681	0.9583	0.9613	0.9514	0.9511

(f) For IEEE 57 bus system (Maximum)

Cases	V_{MAX}						
	Bus No.	Pre insertion of FACTS	Post insertion of FACTS				
			FOA	SFLA	DE	PSO	GA
Case 1	46	1.0760	1.0760	1.0760	1.0760	1.0760	1.0760
Case 2	46	1.0760	1.0760	1.0760	1.0760	1.0760	1.0760
Case 3	46	1.0760	1.0760	1.0760	1.0760	1.0760	1.0760

(g) For IU-NTPS 23 bus system (Minimum)

Cases	V_{MIN}						
	Bus No.	Pre insertion of FACTS	Post insertion of FACTS				
			FOA	SFLA	DE	PSO	GA
Case 1	19	0.9276	1.0103	0.9276	1.0164	0.9651	0.9519
Case 2	19	0.9134	0.9903	0.9705	0.9737	0.9598	0.9515
Case 3	19	0.9394	0.9920	0.9806	0.9904	0.9718	0.9584

(h) For IU-NTPS 23 bus system (Maximum)

Cases	V_{MAX}						
	Bus No.	Pre insertion of FACTS	Post insertion of FACTS				
			FOA	SFLA	DE	PSO	GA
Case 1	22	1.0539	1.0667	1.0539	1.0694	1.0605	1.0546
Case 2	5	1.0224	1.0397	1.0367	1.0374	1.0277	1.0277
Case 3	21	1.0351	1.0399	1.0391	1.0399	1.0386	1.0366

Table 6: Real Power Loss Values comparison (in MW)

(a) For IEEE 14 bus system

Operating Conditions	Pre Insertion of FACTS (Initial)	FOA	SFLA	DE	PSO	GA
Case 1	13.401	10.624	11.409	11.693	12.106	12.189
Case 2	35.042	27.708	28.991	28.875	29.019	30.112
Case 3	24.183	18.882	19.255	19.389	19.771	20.675

(b) For IEEE 30 bus system

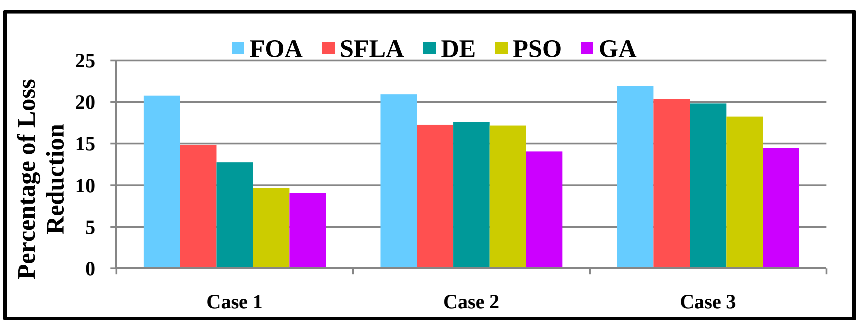
Operating Conditions	Pre Insertion of FACTS (Initial)	FOA	SFLA	DE	PSO	GA
Case 1	17.514	14.016	14.852	16.157	16.504	16.732
Case 2	46.900	44.138	45.797	41.258	43.272	44.195
Case 3	32.569	28.109	29.272	23.234	25.561	27.056

(c) For IEEE 57 bus system

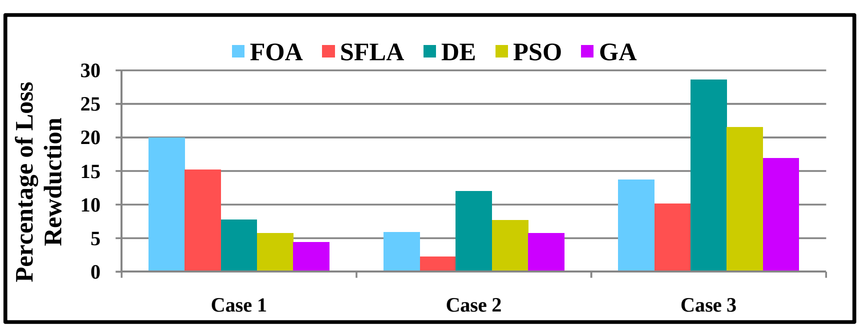
Operating Conditions	Pre Insertion of FACTS (Initial)	FOA	SFLA	DE	PSO	GA
Case 1	27.856	20.307	20.752	21.331	25.037	25.969
Case 2	59.864	48.098	49.103	49.658	54.256	56.672
Case 3	48.549	40.217	41.821	42.018	44.025	45.164

(d) For IU-NTPS 23 bus system

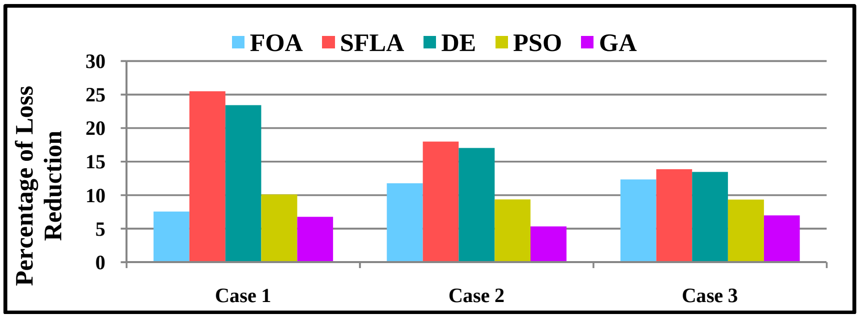
Operating Conditions	Pre Insertion of FACTS (Initial)	FOA	SFLA	DE	PSO	GA
Case 1	13.500	9.012	9.113	9.456	11.243	11.968
Case 2	34.674	25.850	27.425	27.203	28.997	29.758
Case 3	27.381	21.401	22.814	22.113	24.020	24.811



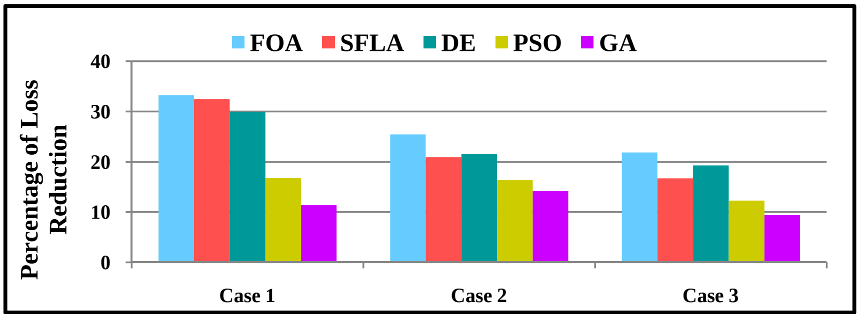
(a) For IEEE 14 bus system



(b) For IEEE 30 bus system



(c) For IEEE 57 bus system



(d) For IU-NTPS 23 bus system

Fig. 6. Percentage of real power loss reduction under all cases

Table 6: Best Location of FACTS Devices

(a) For IEEE 14 bus system

Operating conditions	SSSC		SVC	
	Location (Line No.)	Size [R + jX]	Location (Bus No.)	Size [MVAR]
Case 1	2	0.0171+ j0.1608	14	5.0914
Case 2	4	0.0607 + j0.1227	12	8.0444
Case 3	14	0.0945+ j0.0903	10	7.6987

(b) For IEEE 30 bus system

Operating conditions	SSSC		SVC	
	Location (Line No.)	Size [R + jX]	Location (Bus No.)	Size [MVAR]
Case 1	10	0.0194 + j0.0648	21	6.8015
Case 2	19	0.0309 + j0.1088	14	8.4578
Case 3	17	0.0298 + j0.0955	16	6.9927

(c) For IEEE 57 bus system

Operating conditions	SSSC		SVC	
	Location (Line No.)	Size [R + jX]	Location (Bus No.)	Size [MVAR]
Case 1	34	0.1228 + j0.0398	56	14.0257
Case 2	21	0.0967 + j0.0972	14	19.3207
Case 3	30	0.1058 + j0.1208	29	16.5587

(d) For IU-NTPS 23 bus system

Operating conditions	SSSC		SVC	
	Location (Line No.)	Size [R + jX]	Location (Bus No.)	Size [MVAR]
Case 1	16	0.0889 + j0.1350	13	6.0258
Case 2	8	0.1225 + j0.0955	8	10.7473
Case 3	12	0.1086 + j0.1182	20	8.9641

The reduction rate in real power loss in IEEE 14 and 30 bus systems are 5.301 and 4.460 MW respectively under case 3 operations. In IEEE 57 and IU-NTPS 23 bus systems the reduction rate is 8.332 and 5.980 MW respectively. The real power losses values of proposed method are compared with other evolutionary techniques under all cases are shown in Table 6. The percentage of reduction in real power loss comparison under all cases is depicted in Figure 6. The much reduction in real power loss and increase in voltage magnitudes after the insertion of FACTS devices are highly efficient in relieving a power network from stressed condition and improving voltage stability limit. The most suitable size and location of combinations of FACTS devices to improve the voltage stability limit and real power loss minimization are also given in Table 6 under all cases including both combinations with IEEE 14, 30 and 57 bus test and IU-NTPS 23 bus practical systems. The optimized size of SVC inserted with both combinations is not in larger value which helps to reduce in cost.

7 Conclusion

In this paper optimal location and size of FACTS devices for voltage stability limit improvement and loss minimization through fruit fly algorithm are demonstrated. The voltage stability limit improvement and real power loss minimization are done under three operating cases such as normal, critical loading and line outage contingency conditions. The LQP index is used for voltage stability assessment. The circuit element model of SSSC is considered to improve the voltage stability limit by controlling power flows and maintaining voltage profile. This model is easy to incorporate the effect of SSSC into Newton-Raphson load flow program coding. The performance of FACTS combination in optimal power flow control for voltage stability limit improvement is proved in the results by comparing the system real power loss and voltage profile with and without the devices. It is clear from the numerical results that voltage stability limit improvement and real power loss minimization are highly encouraging. The real power loss minimization and voltage stability limit improvement is remarkable by the combined action of power flow control of SSSC and reactive power compensation by SVC through fruit fly algorithm

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