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Shuffled Frog Leaping Algorithm based Voltage Stability Limit Improvement and Loss Minimization Incorporating FACTS Devices under Stressed Conditions

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ABSTRACT

Recent day power system networks are having high risks of voltage instability problems and several network blackouts have been reported. This phenomenon tends to occur from lack of reactive power supports under heavily stressed operating conditions caused by increased load demand and the fast developing deregulation of power systems across the world. This paper proposes an application of Shuffled Frog Leaping Algorithm (SFLA) based extended voltage stability margin and minimization of loss by incorporating TCSC and SVC (variable susceptance model) devices. The line stability index (LQP) is used to assess the voltage stability of a power system. The location and size of Series connected and Shunt connected FACTS devices are optimized by shuffled frog leaping algorithm. The results are obtained from the IEEE-30 bus test case system under critical loading and single line outage contingency conditions

Keywords

Shuffled Frog Leaping Algorithm, FACTS devices, Line stability index, TCSC, Voltage Stability, SVC.

1. INTRODUCTION

Present day power system are undergoing numerous changes and becoming more complex from operation, control and stability maintenance standpoints when they meet sudden increasing load demand [1]. Voltage stability is concerned with the ability of a power system to maintain acceptable voltage values at all buses in the system under normal conditions and after being subjected to a critical conditions. 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 level. The main factor causing voltage instability is the inability of the power system to meet the demand for reactive power [2]-[4]. Excessive voltage decline can occur following some severe system contingencies and this situation could be aggravated, possibly leading to voltage collapse, by further tripping of more transmission facilities, var sources or generating units due to overloading. Many large interconnected power systems are increasingly experiencing abnormally high or low voltages or voltage collapse. 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 enhance voltage stability margins. [5]-[7]. Voltage instability is one of the phenomena which have result in major blackouts. Recently, several network blackouts have been related to voltage collapses [8].

The Flexible AC Transmission System (FACTS) controllers are capable of supplying or absorption of reactive power at faster rates. The introduction of Flexible AC Transmission System (FACTS) controllers are increasingly used to provide voltage and power flow controls. Insertion of FACTS devices is found to be highly effective in preventing voltage instability [9].Series and shunt compensating devices are used to enhance the Static voltage stability margin.

Voltage stability assessment with appropriate representations of FACTS devices are investigated and compared under base case of study [10]-[12]. One of the shortcomings of those methods is they consider the normal state of the system. 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[13].

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 the critical line with respect to the bus of the system [14]. A.Mohmed et al is made the derivation of line stability index (LQP) used for stability assessment [15]. From the family of evolutionary computation, Shuffled Frog Leaping Algorithm (SFLA) is used to solve a problem of real power loss minimization and Voltage stability maximization of the system.

The SFLA is a meta-heuristic optimization method which is based on observing, imitating, and modeling the behavior of a group of frogs when searching for the location that has the maximum amount of available food [16]. SFLA, originally developed by Eusuff and Lansey in 2003, can be used to solve many complex optimization problems. The author [17] makes a successful implementation of SFLA to water resource distribution network.

Due to the higher capital cost of the TCSC and SVC, the installation is not recommended under all possible line outages. Hence line outage contingency screening and ranking carried out to identify the most critical line during whose outage TCSC and SVC controllers can be positioned and system can be operated under stable condition[18]-[21]. The prime objective of this work is to improve the voltage stability limit and loss minimization of a power system during critical loading and single line outage contingency conditions performed by optimal location and size with TCSC and SVC through shuffled frog leaping algorithm.

2. CRITICAL CONDITIONS

Voltage collapse is a process in which the appearance of sequential events together with the instability in a large area of system can lead to the case of unacceptable low voltage condition in the network, if no preventive action is committed. Occurrence of disturbance or load increasing leads to excessive demand of reactive power. Therefore system will show voltage instability. If additional sources provide sufficient reactive power support, the system will be established in a stable voltage level. However, sometimes there are not sufficient reactive power resources and excessive demand of reactive power can leads to voltage collapse.

Voltage collapse is initiated due to small changes of system condition (load increasing) as well as large disturbances (line or generator unit outage), under these conditions FACTS devices can improve the system security with fast and controlled injection of reactive power to the system. However when the voltage collapse is due to excessive load increasing, FACTS devices cannot prevent the voltage collapse and only postpone it until they reach to their maximum limits. Under these situations the only way to prevent the voltage collapse is load curtailment or load shedding. So critical loading and contingencies are should be considered in voltage stability analysis.

In recent days, the increase in peak load demand and power transfer between utilities has an important issue on power system voltage stability. Voltage stability has been highly responsible for several major disturbances in power system. When load increases, some of the lines may get overloaded beyond their rated capacity and there is possibility to outage of lines. The system should able to maintain the voltage stability even under such a disturbed condition.

3. LINE STABILITY INDEX (LQP)

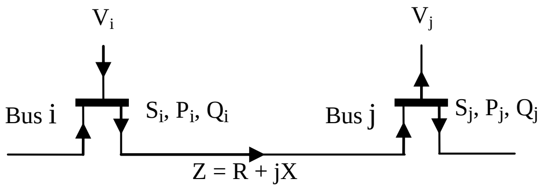

Fig. 1: Single line concept of power transmission

Voltage stability can be assessed in a system by calculating the line based voltage stability index. A Mohamed *et al* [15] derived four line stability factors based on a power transmission concept in a single line. Out of these, the line stability index (LQP) 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 1 illustrates a single line of a power transmission concept.

The power equation can be derived as;

$$\frac{X}{V_i^2}Q_i^2 - Q_i + \left(\frac{X}{V_i^2}P_i^2 + Q_j\right) \qquad (1)$$

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,

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

4. PROBLEM FORMULATION

4.1 Static model of SVC

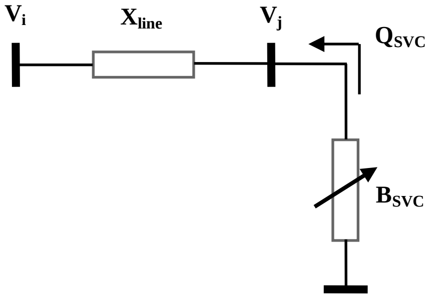

Fig. 2: Variable susceptance model of SVC

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. The circuit shown in figure 2 is used to derive the SVC's nonlinear power equations and the linearised equations required by Newton's load flow method. In general, the transfer admittance equation for the variable shunt compensator is

$$I_{SVC} = jB_{SVC}V_j \qquad (3)$$

And the reactive power is

$$Q_{SVC} = -V_j^2 B_{SVC} \qquad (4)$$

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

$$\begin{bmatrix}\Delta Pj\\ \Delta Qj\end{bmatrix} = \begin{bmatrix}0 & 0\\ 0 & \theta_j\end{bmatrix}\begin{bmatrix}\Delta\theta j\\ \Delta Bsvc/Bsvc\end{bmatrix} \qquad (5)$$

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

$$B_{SVC}^{(i)} = B_{svc}^{(i-1)} + (\Delta B_{SVC}/B_{SVC})^{(i)} B_{SVC}^{(i-1)} \qquad (6)$$

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).

4.2 Static model of TCSC

TCSC is a series compensation component which consists of a series capacitor bank shunted by thyristor controlled reactor. The basic idea behind power flow control with the TCSC is to decrease or increase the overall lines effective series transmission impedance, by adding a capacitive or inductive reactance correspondingly. The TCSC is modeled as variable reactance shown in figure 3. The equivalent reactance of line X_{ij} is defined as:

$$X_{ij} = -0.8X_{line} \le X_{TCSC} \le 0.2X_{line} \qquad (7)$$

where, X_{line} is the transmission line reactance, and X_{TCSC} is the TCSC reactance.

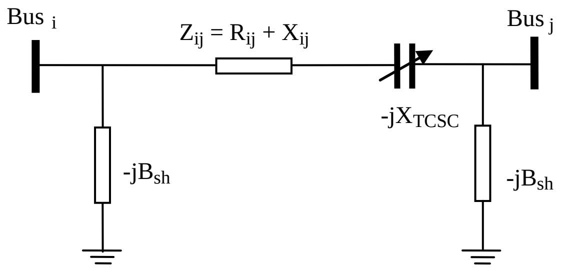

Fig. 3: Model of TCSC

The level of the applied compensation of the TCSC usually varies between 20% inductive and 80% capacitive.

4.3 Objective function

The objective function of this work is to find the optimal rating and location of TCSC and SVC which minimizes the real power loss and maximizes the voltage stability limit, voltage deviation and line stability index. Hence, the objective function can be expressed as

$$F = Minimize[f_1 + \lambda_1 f_2 + \lambda_2 f_3] \tag{8}$$

The term f_1 represents real power loss as

$$f_1 = \sum_{k=1}^{N_L} G_k [V_i^2 + V_j^2 - 2V_i V_j \cos(\delta_i - \delta_j)] \tag{9}$$

The term f_2 represents total voltage deviation (VD) of all load buses as

$$f_2 = VD = \sum_{k=1}^{N_{PQ}} (V_i - V_{ref})^2 \tag{10}$$

The term f_3 represents line stability index (LQP) as

$$f_3 = LQP = \sum_{j=1}^{N_L} LQP_j \tag{11}$$

where λ_1 and is λ_2 are weighing factor for voltage deviation and LQP index and are set to 10.

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

(i) Load Flow Constraints:

$$P_{Gi} - P_{Di} - \sum_{j=1}^{N_B} V_i V_{ij} Y_{ij} \cos(\delta_{ij} + \gamma_j - \gamma_i) = 0 \tag{12}$$

$$Q_{Gi} - Q_{Di} - \sum_{j=1}^{N_B} V_i V_{ij} Y_{ij} \sin(\delta_{ij} + \gamma_j - \gamma_i) = 0 \tag{13}$$

(ii) Reactive Power Generation Limit of SVCs:

$$Q_{ci}^{min} \leq Q_{ci} \leq Q_{ci}^{max}; i \in N_{SVC} \tag{14}$$

(iii) Voltage Constraints:

$$V_i^{min} \leq V_i \leq V_i^{max}; i \in N_B \tag{15}$$

(iv) Transmission line flow limit:

$$S_i \leq S_i^{max}; i \in N_l \tag{16}$$

4.4 Shuffled Frog Leaping Algorithm – An Over view

The SFLA is a meta-heuristic optimization method which is based on observing, imitating, and modeling the behavior of a group of frogs when searching for the location that has the maximum amount of available food. SFLA, originally developed by Eusuff and Lansey in 2003[16], can be used to solve many complex optimization problems, which are nonlinear, non differentiable, and multi-modal. The SFLA combines the benefits of the both the genetic-based memetic algorithm and the social behavior-based PSO algorithm

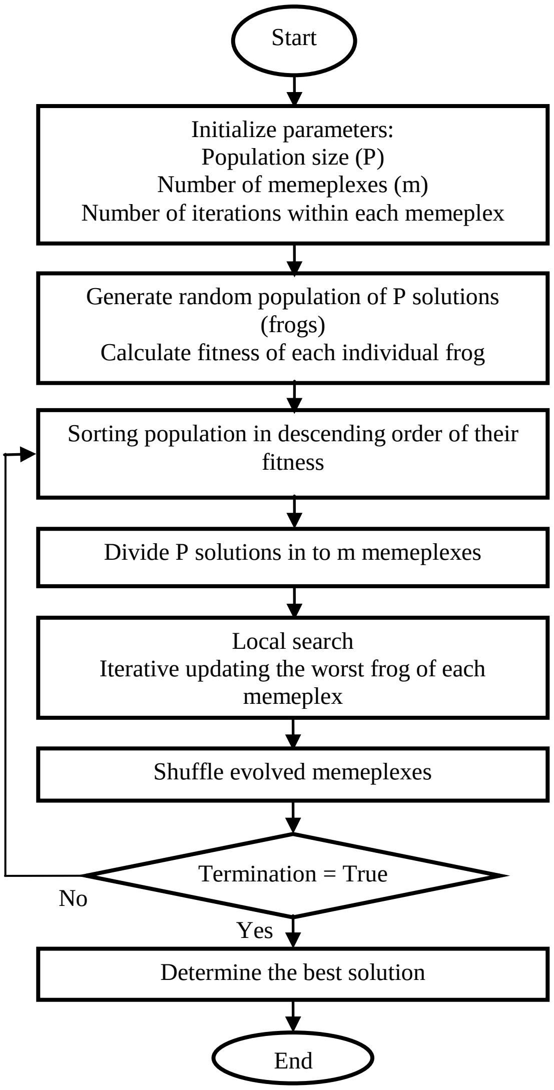

Fig. 4: Flow chart of Shuffled Frog Leaping Algorithm

In SFLA, there is a population of possible solutions defined by a set of virtual frogs partitioned into different groups which are described as memeplexes, each performing a local search. Within each memeplex, the individual frogs hold ideas, which can be infected by the ideas of other frogs. After a defined number of memetic evolution steps, ideas are passed between memeplexes in a shuffling process. The local search and the shuffling process continue until the defined convergence criteria are satisfied. The flow chart of shuffled frog leaping algorithm is depicted in fig 4.

In the first step of this algorithm, an initial population of P frogs is randomly generated within the feasible search space. The position of the *i* th frog is represented as $X_i = (X_{i1}, X_{i2} \ldots X_{iD})$, where *D* is the number of variables. Then, the frogs are sorted in descending order according to their fitness.

Afterwards, the entire population is partitioned into *m* subsets referred to as memeplexes each containing *n* frogs (i.e., *P* = *m* x *n*). The strategy of the partitioning is as follows:

The first frog goes to the first memeplex, the second frog goes to the second memeplex, the m th frog goes to the m th memeplex, the (m + 1) th frog goes back to the first memeplex, and so forth.

In each memeplex, the positions of frogs with the best and worst fitnesses are identified as X_b and X_w, respectively. Also the position of a frog with the global best fitness is identified as X_g.

Then, within each memeplex, a process similar to the PSO algorithm is applied to improve only the frog with the worst fitness (not all frogs)in each cycle. Therefore, the position of the frog with the worst fitness leaps toward the position of the best frog, as follows:

$$D_i = rand \times (X_b - X_w) \qquad (17)$$

$$X_w^{new} = X_w^{old} + D_i \ (D_{i\,min} < D_i < D_{i\,max}) \qquad (18)$$

where D_{imax} and D_{imin} are the maximum and minimum step sizes allowed for a frog's position, respectively.

If this process produces a better solution, it will replace the worst frog. Otherwise, the calculations in (17) and (18) are repeated but are replaced but X_b is replaced by X_g. If there is no improvement in this case, a new solution will be randomly generated within the feasible space to replace it. The calculations will continue for a specific number of iterations. Therefore, SFLA simultaneously performs an independent local search in each memeplex using a process similar to the PSO algorithm. After a predefined number of memetic evolutionary steps within each memeplex, the solutions of evolved memeplexes are replaced into new population shuffling process.

The shuffling process promotes a global information exchange among the frogs. Then, the population is sorted in order of decreasing performance value and updates the population best frog's position, repartition the frog group into memeplexes, and progress the evolution within each memeplex until the conversion criteria are satisfied. Usually, the convergence criteria can be defined as follows:

The relative changes in the fitness of the global frog within a number of consecutive shuffling iterations are less than a pre-specified tolerance.

The maximum predefined number of shuffling iteration has been obtained. The optimal parameter values of shuffled frog leaping algorithm shown in table 1.

4.5 Implementation of Shuffled Frog Leaping Algorithm

Step 1: Select m the number of memeplexes and n the number of frogs in each memeplex. Total frogs $P = m$ x n. Generate required population (X_i), i=1 to P, by random generation. Evaluate the fitness f (X_i) of each frog and arrange them in ascending order.

Step2: According to the fitness value, arrange the frogs in to memeplexes (The first frog goes to the first memeplex, the second frog goes to the second memeplex, the m th frog goes to the m th memeplex, the (m + 1) th frog goes back to the first memeplex, and so forth.). Find the position of frogs with the best, worst fitnesses identified as X_b and X_w respectively and the global best X_g for all m-memeplexes.

Step 3: Improving worst frog position: The local exploration is implemented in each memeplex, i.e., the worst performance frog (X_w) in the memeplex is updated according to the following modification rule: $Di = rand$ x (X_b - X_w) , i=1 to m. Accept Di if it is within D_{min} and D_{max}, i.e.; $D_{min} < D_m < D_{max}$, otherwise set to minimum or maximum limits of Di. '*rand*' is the random number generated between 0 and 1. The new position of the frog is updated as

$X_w^{new} = X_w^{old} + D_i$; ($D_{min} < D_m < D_{max}$). Then recalculate fit of this frog.

Step 4: If the fitness of X_w^{new} is more than the fitness of X_w^{old} then accept the X_w^{new} . Else generate new D_i value with respect to global X_g:

D_i = *Rand x* (X_b - X_w). Accept D_i if it is D_{min} *and* D_{max}, otherwise set to minimum or maximum limits of D_i. The new position is computed by

$X_w^{new} = X_w^{old} + D_i$. Again compute fitness of this frog.

If the fitness of X_w^{new} is more than the fitness of X_w^{old} then accept the X_w^{new}. Else randomly generate the new frog in place of X_w within the acceptable frog limits.

Step 5: Repeat step 3 and 4 for all memeplexes. This completes one iteration. Now shuffle the frogs as per step 2.

Step 6: Repeat algorithm until the solution criterion is met or maximum number of iterations are completed. The solution criterion is $[|X_w^{new}| - |X_w^{old}|] < \epsilon$, where ϵ is the convergence tolerance. Stop.

Table 1. Optimal values of SFLA parameters

Parameters	Optimal value
Number of frogs	50
Number of memeplexes	5
Number of frogs per memeplexes	10
No of iterations	200

5. RESULTS AND DISCUSSIONS

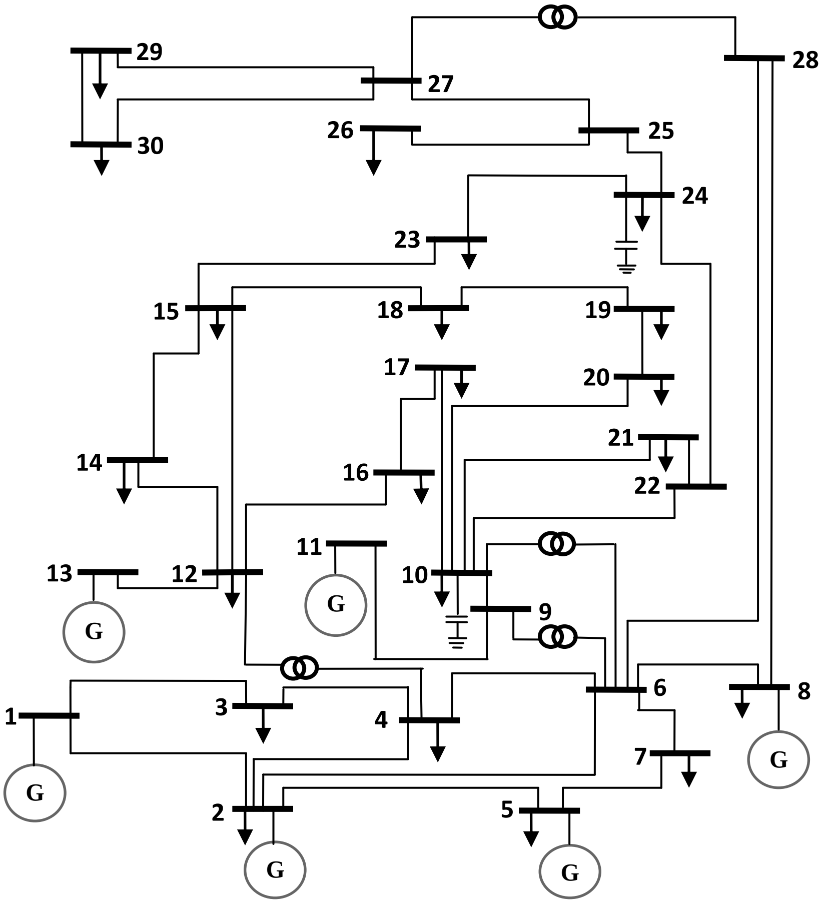

Figure 5: One line diagram of IEEE 30 Bus Test System

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 in the IEEE 30 bus test system shown in figure 5.The line data and bus data are taken from the standard power system test case archive. The system has 6 generator buses, 24 load buses and 41 transmission lines. System data and results are based on 100 MVA and bus1 is the reference bus. In order to verify the presented models and illustrate the impacts of TCSC and SVC study, two different stressed conditions are considered as mentioned below.

Case 1: The system with 50 % increased load in all the load buses is considered as a critical condition due to increased load. Loading of the system beyond this level, results in poor voltage profile in the load buses and unacceptable real power loss occurs.

Case 2: Contingency analysis carried out on the IEEE 30 bus system shows that line number 5 connected between buses 2 and 5 is the most critical line. The system with outage of line number 5 is taken as stressed conditions due to line outage.

In case 1, the Newton – Raphson program is repeated with presence and absence of TCSC and SVC devices. The LQP values of all lines under normal and critical loading conditions are depicted in figures 6 and 7 respectively.

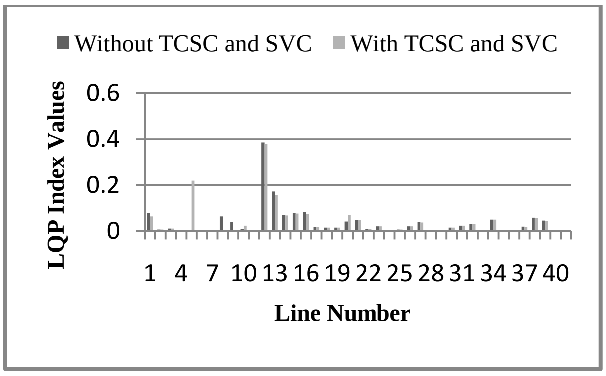

Figure 6: LQP index values under normal loading

In case 2, the line outage is ranked according to the severity and the severity is taken on the basis of the line stability index values (LQP) and such values are arranged in descending order. The maximum value of index indicates most critical line outage. Line outage contingency screening and ranking is carried out on the test system and the results are shown in table 2. It is clear from the results that outage of line number 5 is the most critical line outage and this condition is considered for voltage stability improvement. Outage of other lines has no much impact on the system and therefore they are not given importance.

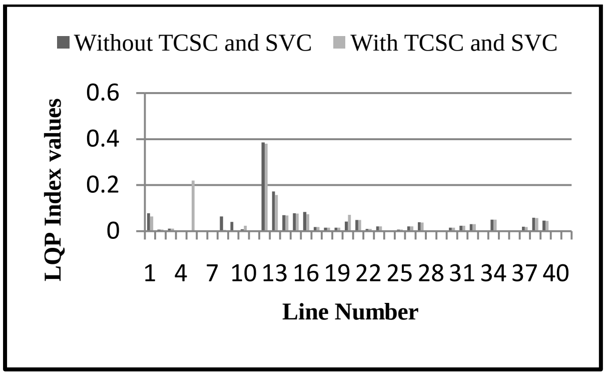

Figure 7: LQP index values under critical loading

The details of voltage profiles in all cases are shown in table 3 and the corresponding values of LQP index are depicted in figure 8. It is clear from the table that the voltage profile is improved considerably. The sum of LQP values in all cases is also depicted in figure 9.

Table 2. Contingency Ranking

Rank	Line Number	LQP index Values
1	5	0.9495
2	9	0.6050
3	2	0.4993
4	4	0.4968
5	7	0.4693
6	6	0.3965
7	10	0.3960
8	15	0.3943
9	3	0.3940
10	11	0.3917

Table 3. Voltage Profile Values of all cases

Bus No.	Normal Loading		Critical Loading		Single Line Outage Contingency Condition	
	Without TCSC and SVC	With TCSC and SVC	Without TCSC and SVC	With TCSC and SVC	Without TCSC and SVC	With TCSC and SVC
1	1.0600	1.0600	1.0600	1.0600	1.0600	1.0600
2	1.0400	1.0430	1.0030	1.0030	1.0430	1.0430
3	1.0217	1.0225	0.9745	0.9764	1.0069	1.0105
4	1.0129	1.0139	0.9581	0.9605	0.9958	1.0003
5	1.0100	1.0100	0.9600	0.9600	0.9600	0.9600
6	1.0121	1.0130	0.9553	0.9574	0.9909	0.9977
7	1.0035	1.0040	0.9438	0.9451	0.9661	0.9753
8	1.0100	1.0100	0.9600	0.9600	0.9900	1.0000
9	1.0507	1.0548	0.9923	1.0020	1.0388	1.0425
10	1.0438	1.0517	0.9722	0.9856	1.0366	1.0345
11	1.0820	1.0820	1.0520	1.0620	1.0820	1.0820
12	1.0576	1.0612	1.0004	1.0101	1.0495	1.0520
13	1.0710	1.0710	1.0410	1.0510	1.0710	1.0710
14	1.0429	1.0480	0.9754	0.9859	1.0339	1.0367
15	1.0385	1.0449	0.9670	0.9786	1.0288	1.0313
16	1.0445	1.0500	0.9769	0.9882	1.0341	1.0372
17	1.0387	1.0459	0.9650	0.9778	1.0262	1.0299
18	1.0282	1.0352	0.9489	0.9614	1.0167	1.0201
19	1.0252	1.0326	0.9434	0.9563	1.0131	1.0167
20	1.0251	1.0366	0.9493	0.9623	1.0167	1.0203
21	1.0293	1.0414	0.9489	0.9627	1.0163	1.0202
22	1.0353	1.0436	0.9572	0.9793	1.0215	1.0257
23	1.0291	1.0405	0.9488	0.9627	1.0163	1.0202
24	1.0237	1.0324	0.9369	0.9543	1.0091	1.0136
25	1.0202	1.0262	0.9328	0.9451	1.0023	1.0081
26	1.0025	1.0086	0.9034	0.9161	0.9844	0.9903
27	1.0265	1.0308	0.9446	0.9535	1.0068	1.0134
28	1.0109	1.0120	0.9510	0.9535	0.9901	0.9976
29	1.0068	1.0111	0.9109	0.9202	0.9866	0.9933
30	0.9953	0.9997	0.8915	0.9010	0.9750	0.9817

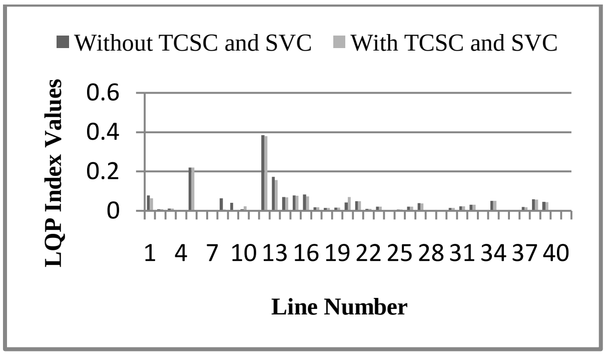

Figure 8: LQP index values under single line outage contingency condition

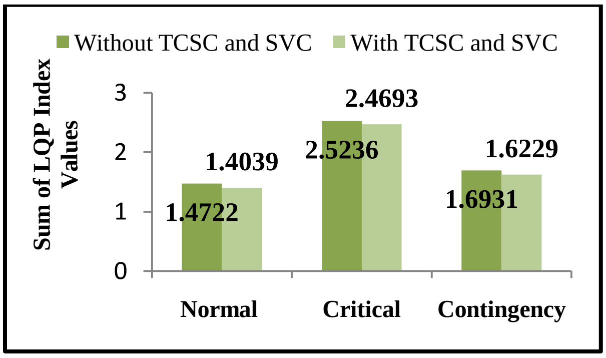

Figure 9: Sum of LQP index values in all cases

For installation of TCSC, the candidate positions are the lines without tap changing transformer. The lines 11, 12, 15 and 36 are with tap changing transformer and not considered for positioning of TCSC. Locating TCSC on different branches is tried one by one based on the proposed algorithm. SVC can be connected only to load buses. Buses 1, 2, 5,8,11 and 13 are generator buses and therefore not considered as possible locations for SVC. When the global best position for an TCSC is a line with tap changing transformer or global best position of an SVC is a generator bus then the position is relocated to a geographically closer line without transformer or load bus. The most suitable location for TCSC to control power flow is found to be line number 21 for normal loading and line number 22 and 7 for critical loading and line outage contingency conditions respectively. Similarly SVC to improve voltage profile are found to be bus number 2 for normal loading and bus number 20 for both critical loading and line outage contingency conditions.

In loss minimization point of view through insertion of TCSC and SVC, the real power loss under normal loading is decreased by 0.116 MW which is 0.67% of total real power loss. Similarly under critical loading and line outage contingency conditions the real power loss decreased by 0.259

Table 4. Real and Reactive power Loss Values for all cases

Loss Parameters	Normal Loading		Critical Loading		Single Line Outage Condition	
	Without TCSC and SVC	With TCSC and SVC	Without TCSC and SVC	With TCSC and SVC	Without TCSC and SVC	With TCSC and SVC
P_{loss} (MW)	17.514	17.398	46.900	46.641	32.569	32.076
Q_{loss} (MVAR)	68.691	67.523	180.837	180.312	112.229	110.298

Table 5. Best Location of TCSC and SVC

Cases	TCSC		SVC	
	Location	Degrees of Compensation	Location	Size (MVAR)
Normal loading	Between buses 16 and 17 (Line 21)	-0.0873	Bus No. 2	9.2532
Critical loading	Between buses 15 and 18 (Line 22)	-0.2811	Bus No. 20	8.2923
Single line outage contingency	Between buses 4 and 6 (Line 7)	-0.6438	Bus No. 20	9.8308

MW and 0.493 MW respectively. The percentages of reduction under these cases are 0.55% and 1.51 % respectively. The real and reactive power losses under all cases are shown in table 4. The reduction in real power loss and increase in voltage magnitudes after the insertion of TCSC and SVC proves that FACTS devices are highly efficient in relieving a power network from stressed condition and improving voltage stability limit.

The best location and size (Degrees of compensation) of TCSC under all conditions are shown in table 5. The location of TCSC is quiet different in all cases. But the best location of SVC is same under critical loading and contingency conditions and not same under normal loading condition. The size of SVC is not so large and lies between 8.2923 MVAR to 9.8308 MVAR which helps to minimize the cost of VAR devices. The size of SVC is least under critical loading condition.

6. CONCLUSIONS

In this paper, optimal location of TCSC and SVC for voltage stability limit improvement and loss minimization are demonstrated. The voltage stability limit improvement and real power loss minimization are done under critical loading and line outage contingency conditions. The LQP index is used for voltage stability assessment. The reactance model of TCSC is considered to improve the voltage stability limit by controlling power flows and maintaining voltage profile. The performance of TCSC and SVC 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 is highly encouraging. The voltage stability limit improvement is by the combined action of power flow control of TCSC and reactive power compensation by SVC.

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