Performance Evaluation of TCSC and SVC on Voltage Stability Limit Improvement and Loss Minimization under Most Critical Line Outaged Condition

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ABSTRACT

Due to the ever increasing demand for power, environmental constraints in expansion of transmission networks and the emerging scenario of restructuring of power system networks, the transmission lines are prone to be operated under heavily stressed conditions. In such a heavily stressed condition, there is a risk of line outage and the consequent voltage instability. This necessitates voltage stability limit improvement under probable line outage contingency conditions to keep the system under voltage secured conditions. Flexible Alternating Current Transmission System (FACTS) devices are found to be encouraging in improving voltage stability limit of power systems. In this paper, optimal location of TCSC and SVC are considered for reducing line losses and improving voltage stability limit. Amount of increased reactive power generation and line losses are taken as indicators of stressed conditions of a power system. The optimal location and sizing of TCSC and SVC are identified through Particle Swarm Optimization (PSO) algorithm. The proposed method is tested in IEEE 30 bus test system and results obtained are proving the validity of the work.

Keywords - **FACTS, TCSC, SVC, Contingency, PSO, Voltage Stability improvement**

I. INTRODUCTION

The present day power systems are forced to be operated much closer to stability limits due to ever increasing load demand, the environmental constraints in expansion of transmission networks and transmission open access in a restructured power market. In such a stressed condition, the system may enter into voltage instability problem and it has been found responsible for several block outs across the world [1]-[2]. A power system needs to be with sufficient reactive power capability to remain voltage secured even under highly stressed conditions.

In a deregulated environment, the optimum bidders are chosen only based on real power cost characteristics and this results in reactive power shortage and ultimately the probable voltage instability. Transmission lines, in a deregulated environment, are operated under heavily loaded conditions and it results in increased voltage drop and is in high risks of outages. To ensure uninterrupted and quality power supply to the consumers the power system should be stable even under contingency conditions.

The introduction of Flexible AC Transmission System (FACTS) controllers [3] are increasingly used to provide voltage and power flow controls. Insertion of FACTS devices is found to be highly effective in preventing voltage instability [4]. However, the benefits and performance of FACTS controllers are determined by their location and size [5]. Owing to high cost, the number of FACTS devices to be used should be minimized and their benefits may be maximized through efficient optimization methods [6].

The effect of TCSC and SVC devices on voltage collapse phenomenon in power systems to increase system loadability is studied and the location and size of the devices are optimized [7]. The maximization of static voltage stability margin and the reduction of total real power losses are discussed in [8]. Proper placement of Static VAR compensator (SVC) and Thyristor Controlled Series compensator (TCSC) reduces transmission losses, increases the available transfer capacity, and improves the voltage profile. Paper [9] presents an optimal placement of SVC and TCSC to determine SVC and TCSC locations and control parameters for minimization of transmission loss. It is well known that voltage stability enhancement margin is interrelated with real power loss. To improve voltage stability limit, location and placement of FACTS devices is a major task. In paper [10], voltage stability assessment with appropriate representation of SVC and TCSC is investigated.

In most of the previous works on voltage stability improvement, only normal operating condition is considered [11]-[12] but voltage instability is usually caused by contingencies. Critical contingency is considered and conventional methods are used to install FACTS devices for improvement of voltage stability in some recent works [13]-[15]. In those works, the contingency severity is done based on the level of loading. But these methods do not deal with the likelihood of the occurrence of contingency. In this work, the severity of a line outage is measured by considering the amount of reactive power generation, as stressed condition implies increased reactive power demand. The Fast Voltage Stability Index (FVSI) [16] is used to assess the voltage stability. The simple and easy to implement swarm intelligent algorithm of Particle Swarm Optimization technique is used to determine the optimal location and sizing of TCSC and SVC devices. The objective of this work is improve the voltage stability and reduce the line losses by providing reactive power support by TCSC and SVC devices under the most critical line outage contingency condition.

II. VOLTAGE STABILITY INDEX FORMULATION

Voltage stability can be assessed in a system by calculating the line based voltage stability index. In this research work, the voltage stability index derived in [16] is used. The value of line index shows the voltage stability of the system. The indicator takes values between 0 and 1. 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 . This indicator can be calculated quickly and provides acceptable results.

The voltage stability index developed is derived by first obtaining the current equation through a line in a two bus system shown in figure 1.

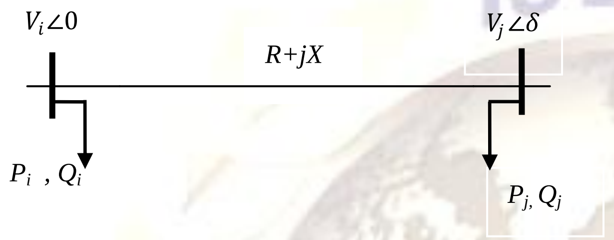

Figure 1: Sample Two bus system

Where
V_i and V_j = Sending end and receiving end voltage magnitudes
δ = The angle difference $(\delta_i - \delta_j)$
P_i and P_j = Sending end and receiving real powers
Q_i and Q_j = Sending end and receiving end reactive powers
Considering the sending bus (bus *i*) as the reference then the general current equation can be written as;

$$I = \frac{V_i\angle 0 - V_j\angle\delta}{R + jX} \quad (1)$$

Where *R*=Resistance of the line and *X*=Reactance of the line

$$V_j^2 - \left(\frac{R}{X}sin\delta + cos\delta\right)V_iV_j + \left(X + \frac{R^2}{X}\right)Q_j = 0 \quad (2)$$

The above one is a quadratic equation in V_j and it can be solved as shown in equation (3)

$$V_j = \left(\frac{R}{X}sin\delta + cos\delta\right)V_i \pm \sqrt{\left[\left(\frac{R}{X}sin\delta + cos\delta\right)V_i\right]^2 - 4\left(X + \frac{R^2}{X}\right)Q_j} \quad (3)$$

The root is determined by setting the discriminate equal to or greater than 0 as follows.

$$\frac{4Z^2Q_jX}{(V_i)^2(Rsin\delta + Xcos\delta)} \le 1 \quad (4)$$

Normally $\delta \approx 0$; $Rsin\delta \approx 0$; and $Xcos\delta \approx X$ and hence

$$FVSI_{ij} = \frac{4Z^2Q_j}{V_i^2X} \quad (5)$$

III. PROBLEM FORMULATION

1. 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 2. The equivalent reactance of line X_{ij} is defined as:

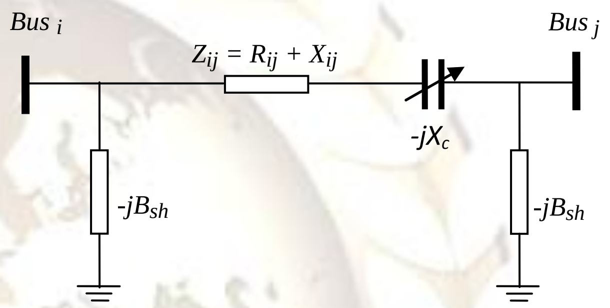

Figure 2: Model of TCSC

$$X_{ij} = -0.8X_{line} \le X_{TCSC} \le 0.2X_{line} \quad (6)$$

where, X_{line} is the transmission line reactance, and X_{TCSC} is the TCSC reactance. The level of the applied compensation of the TCSC usually varies between 20% inductive and 80% capacitive.

2. Static model of SVC

The SVC is modeled as a variable reactive power source connected to a bus in a system. The effect of SVC is incorporated in power flow problem as reactive power generation/absorption. The range of reactive power generation is limited between maximum and minimum values of -50 MVAR to +50 MVAR to keep the size minimum for reducing the cost of SVC.
The reactive power generated by an SVC is given by

$$Q_{SVC}^{min} \le Q_{SVC} \le Q_{SVC}^{max} \quad (7)$$

3. Contingency Ranking

Line outage screening and ranking is carried out in the system considered to identify the most critical line outage. All the possible line outages of the system are considered one at a time. The line whose outage leaves the system with decreased voltage level and increased reactive power generation is identified as the most critical line. The step by step procedure for contingency ranking is given below.

Step1: Input the system data like number of buses, number of lines and number of tap changer transformer etc.

Step2: Consider the line outages one by one and the corresponding reactive power generation and losses are obtained by running load flow.

Step3: The reactive power generation and losses corresponding different line outages are arranged in descending order.

Step4: The most critical line is identified as the line whose outage results in the highest value of reactive power generation and losses (highly stressed condition).

4. 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, voltage deviation and line stability index. Hence, the objective function can be expressed as:

$$F = Minimize[f_1 + \lambda_1 f_2 + \lambda_2 f_3] \quad (8)$$

The term f_1 represents real power loss as:

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

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

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

The term f_3 represents fast voltage stability index (FVSI) as:

$$f_3 = FVSI = \sum_{j=1}^{N_L} FVSI_j \quad (11)$$

Where, λ_1 and is λ_2 are weighing factor for voltage deviation and FVSI index and are set to 10.

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

(i) Load Flow Constraints:

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

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

(ii) Reactive Power Generation Limit of SVCs:

$$Q_{sh}^{min} \le Q_{sh} \le Q_{sh}^{max}; i \in N_{SVC} \quad (14)$$

(iii) Voltage Constraints:

$$V_i^{min} \le V_i \le V_i^{max}; i \in N_B \quad (15)$$

(iv) Transmission line flow limit:

$$S_i \le S_i^{max}; i \in N_l \quad (16)$$

5. Implementation of PSO Algorithm

PSO is an evolutionary computation technique developed by Eberhart and Kennedy in 1995, and was inspired by the social behavior of bird flocking and fish schooling [16]. PSO has its roots in artificial life and social psychology as well as in engineering and computer science. It utilizes a population of individuals, called particles, which fly through the problem hyperspace with some given initial velocities. In each iteration the velocities of the particles are stochastically adjusted considering the historical best position of the particles and their neighborhood best position; where these positions are determined according to some predefined fitness function. Then, the movement of each particle naturally evolves to an optimal or at least near-optimal solution.

Each particle keeps track of its coordinates in the problem space which are associated with the best solution (fitness) it has achieved so far. The fitness value is also stored. This value is called P_{best}. When a particle takes all the population as its topological neighbors, the best value is a global best and is called G_{best}. After finding the two best values, the particle updates its velocity and positions with following equation (17) and (18).

$$V_i^{k+1} = W * V_i^k + C_1 * rand_1 * (P_{besti} - S_i^k) + C_2 * rand_2 * (G_{best} - S_i^k) \quad (17)$$

$$S_i^{k+1} = S_i^k + V_i^{k+1} \quad (18)$$

Where

V_i^k= Velocity of agent *i* at k^{th} iteration

V_i^{k+1}= Velocity of agent *i* at $(k+1)^{th}$ iteration

W = The inertia weight

$C_1 = C_2$ = individual and social acceleration constants (0 to 3)

$rand_1 = rand_2$ = random numbers (0 to1)

S_i^k = Current position of agent *i* at k^{th} iteration

S_i^{k+1}= Position of agent *i* at $(k+1)^{th}$ iteration

$P_{best\ i}$ = Particle best of agent *i*

G_{best} = Global best of the group

5.1 Particle Definition:

Each particle is defined as a vector containing the SVC Bus location number and its size.

Particle: [@ Φ]

Where

@ = the SVC bus location number.

Φ = the SVC size.

5.2 PSO Parameters:

The performance of the PSO is greatly affected by its parameter values. Therefore, a way to find a suitable set of parameters has to be chosen. In this case, the selection of the PSO parameters follows the strategy of considering different values for each particular parameter and evaluating its effect on the PSO performance. The optimal values for the PSO parameters are shown in Table 1.

5.3 Number of Particles:

There is a trade-off between the number of particles and the number of iterations of the swarm and each particle fitness value has to be evaluated using a power flow solution at each iteration, thus the number of particles should not be large because computational effort could increase dramatically. Swarms of 5 and 25 particles are chosen as an appropriate population sizes.

5.4 Inertia Weight:

The inertia weight is linearly decreased. The purpose is to improve the speed of convergence of the results by reducing the inertia weight from an initial value of 0.9 to 0.1 in even steps over the maximum number of iterations as shown in equation 19.

$$W_i = 0.9 - 0.8\left(\frac{iter - 1}{max\ iter - 1}\right) \quad (19)$$

Where,
W_i = The inertia weight at iteration *i*.
iter = the iteration number.
max*iter* = The maximum number of iterations.

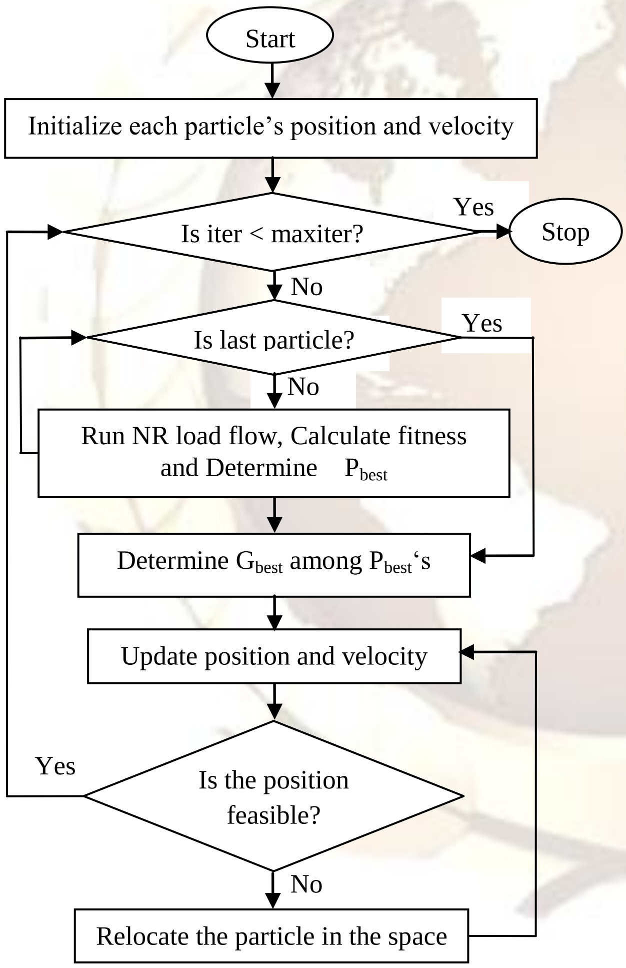

Figure 3: Flow chart for the PSO

5.5 Acceleration constants:

A set of three values for the individual acceleration constants are evaluated to study the effect of giving more importance to the individual's best or the swarm's best: C_1 = {1.5, 2, and 2.5}. The value for the social acceleration constant is defined as: $C_2 = 4 - C_1$.

5.6 Number of Iterations:

Different numbers of iterations {10, 25, and 50} are considered in order to evaluate the effect of this parameter on the PSO performance.

5.7 Values for Maximum velocity:

In this case, for each particle component, values for the maximum velocity have to be selected. Based on previous results, a value of 7 is considered as the maximum velocity for the location line number.

5.8 Feasible Region Definition:

There are several constraints in this problem regarding the characteristics of the power system and the desired voltage profile. Each of these constraints represents a limit in the search space .Therefore the PSO algorithm has to be programmed so that the particles can only move over the feasible region. The flow chart is depicted in figure 3.

5.9 Integer PSO:

For this particular application, the position of the particle is determined by an integer number (Bus number). Therefore the particles' movement given by [17] is approximated to the nearest integer numbers. Additionally, the location number must not be a generator bus. If the location is a generator bus, then the particle component regarding position is changed to the geographically closest load bus.

5.10 Optimal Parameter Values:

Table 1. Optimal values of PSO parameters

Parameter	Optimal Values
Number of particles	20
Inertia weight	Linearly decreased
Individual acceleration constant	2.5
Social acceleration constant	2.0
No of iterations	50
Velocity bounds	{-3,7}
$rand_1$	0.3
$rand_2$	0.2

IV SIMULATION RESULTS AND DISCUSSIONS

The proposed PSO algorithm is run in the Matlab 7.8 environment using 2.9 GHz Intel Core 2 Duo processor based PC. The method is tested in the IEEE 30 bus test system depicted in figure 4. The line data and bus data are taken from the test case archives [18]. The system has 6 generator buses, 24 load buses and 41 transmission lines. Contingency is considered by imposing outage of all 41 lines one at a time. Operation of the system under outage of lines 1, 13, 16 and 34 forces the system into unstable condition that is when one of those lines is outaged the NR load flow fails to converge.

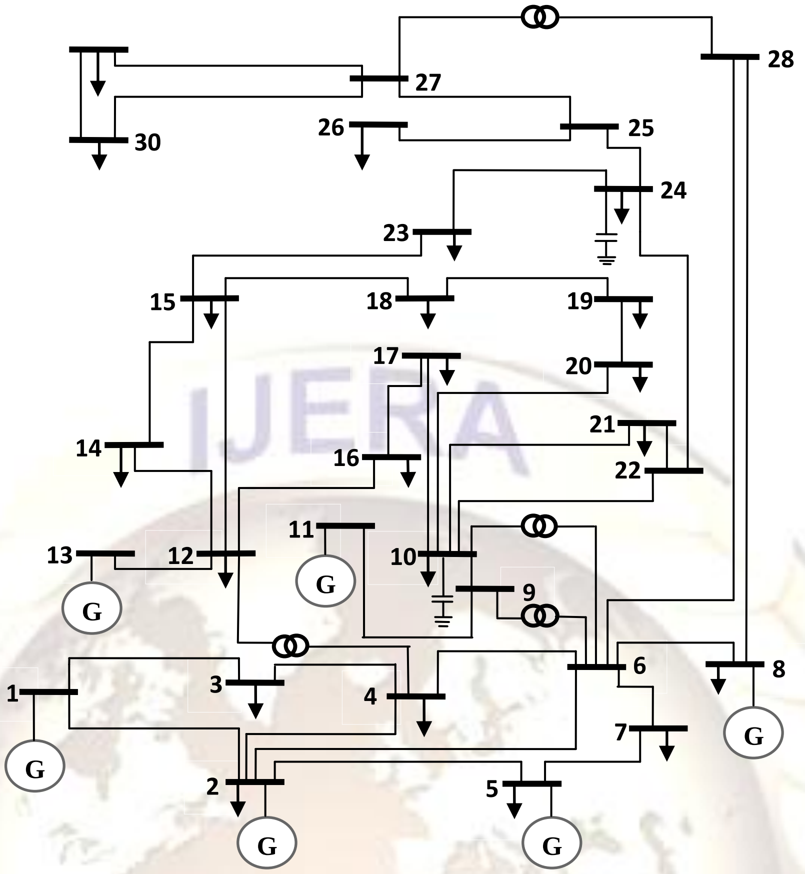

Figure 4: One line diagram of IEEE 30 bus test system

Installations of FACTS devices naturally improve the voltage stability of a power system. But, keeping in mind, the cost of FACTS devices and the optimization task, the number of devices and their sizes are minimized. Taking corrective actions to keep the system voltage secured under all possible line outage contingency will not be economical or it may not be necessary. Therefore, only the most critical line outage contingency is considered

The most critical contingency is identified as outage of line 5 from Table 2 since its outage leaves the system under highly stressed condition with regard to increased reactive power generation, voltage drop and line losses. Outage of other lines has no much impact on the system and therefore they are not given importance. The lines with next levels of criticality are also shown in Table 2 with total P loss and Q generation.

TCSC and SVC are taken for voltage stability enhancement under contingency condition. Transmission lines 11, 12, 15, and 36 are with tap changer transformers and therefore not suitable for positioning of TCSC. Only the remaining 37 lines are considered as candidate locations. The network has 6 generator buses and they are not considered for locating SVC, leaving 24 other possible locations (load buses) for positioning of SVC. The effectiveness of TCSC and SVC in voltage stability enhancement is discussed as three different cases as follows

Case 1: With TCSC only

During the outage of line 5, the global best position for location of TCSC is found to be line (6-8). When TCSC is located at this line it results in enhancement of voltage stability limit by reducing the real power loss, the value of FVSI and the minimization of voltage deviation at all the load buses. The voltage profile improvement is illustrated well in figure 5.

Table 2. Critical lines ranking

Rank	Outage Line no	Total P_{loss} (MW)	Total Q_{gen} (MVAR)
1	5	74.948	330.629
2	2	59.768	289.547
3	4	58.650	285.712
4	7	45.707	253.859
5	6	44.196	250.920

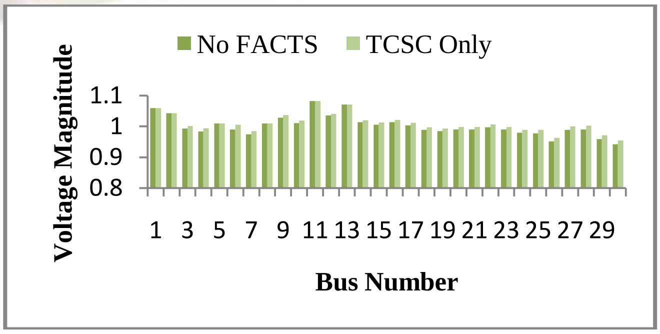

Figure 5: Voltage profile improvement with TCSC only

Table 3: Global best solution, FVSI, P_{loss} and Q_{gen} for all cases

Type of Device	Global Best Position	Global Best Size	Line Reactance		Sum of FVSI	Sum of P_{loss} (MW)	Sum of Q_{gen} (MVAR)
			X_{old}	X_{new}			
Without Device	-	-	-	-	4.7264	74.948	330.629
With TCSC	Line No. 10 (6-8)	-	0.0420	0.0152	3.8600	73.947	323.102
With SVC	Bus No.7	25.852	-	-	4.1869	73.205	325.451
With TCSC and SVC	TCSC at Line No. 10 (6-8) and SVC at Bus No.7	45.584	0.0420	0.0152	3.6255	71.563	317.332

Case 2: With SVC only

Positioning of an SVC at bus 7, during outage of line 5, minimizes the voltage deviation at all the load buses. This is illustrated well in figure 6. More weightage is given for minimization of real power loss than voltage deviation and therefore the voltage profile improvement is less than the usual level by SVCs.

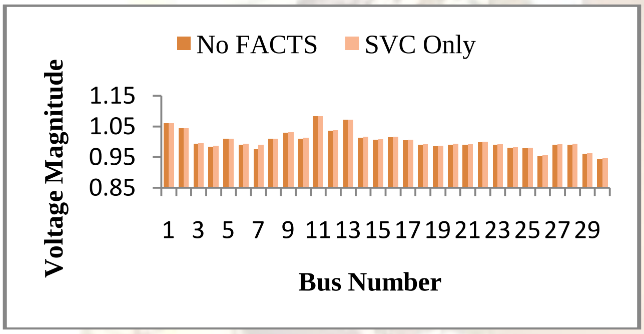

Figure 6: Voltage profile improvement with SVC only

Case 3: With both TCSC and SVC

For effective voltage stability improvement, all the three parameters of FVSI, total real power loss and total reactive power generation are to be controlled. It has been seen that TCSC is capable in control of FVSI and total reactive power generation and SVC, the total real power loss. By using a TCSC and an SVC the voltage stability improvement goal is well accomplished. The global best position for location of SVC in the series compensated system is bus number 7.

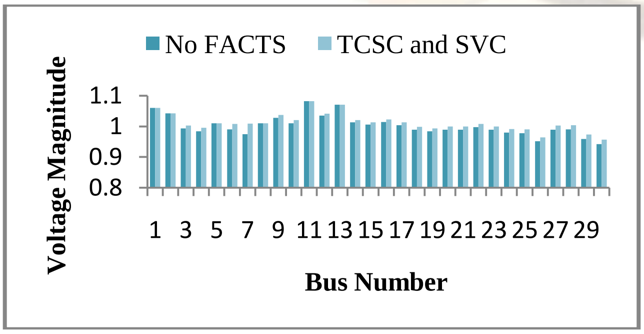

Figure 7: Voltage profile improvement with TCSC and SVC

It can be seen that the position of SVC is consistent regardless of whether TCSC is included or not. Positioning of an SVC at the suitable bus improves the voltage stability limit and minimizes the voltage deviation at all the load buses. The voltage profile improvement is depicted in figure 7.

The reduction in the sum of FVSI of all the lines, total real power loss and total reactive power generation due to the presence of TCSC, SVC and both are shown in Table 3. The reduction in the value of sum of FVSI is a clear indication of voltage stability limit enhancement in all cases. The sum of FVSI values in all cases are depicted in figure 8.

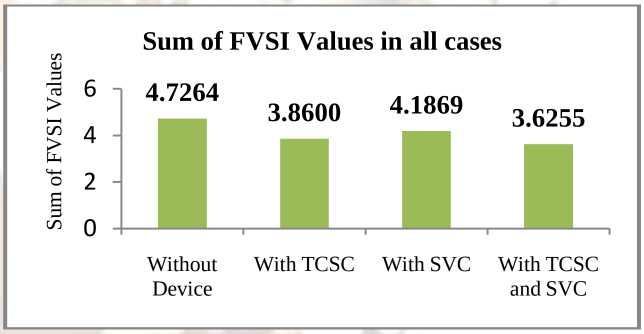

Figure 8: Sum of FVSI values in all cases

The insertion of TCSC and SVC devices also reduces the level of stressed condition of the system by reducing the total real power loss and reactive power generation. Also the sum of real power loss and reactive power generation values in all cases are depicted in figure 9 and figure 10 respectively.

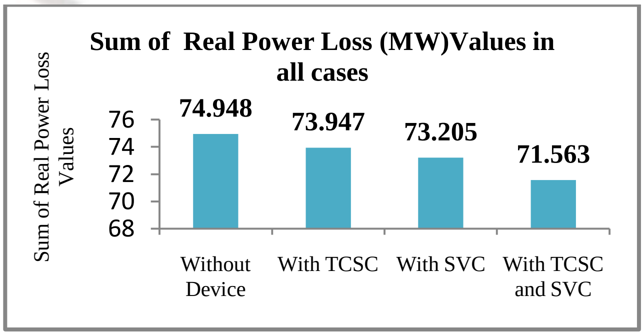

Figure 9: Sum of Real power loss values in all cases

In case 1 the total real power loss and reactive power generation are reduced by 1.001 MW and 7.527 MVAR respectively. The percentages of reduction are 1.34% and 2.28% respectively.

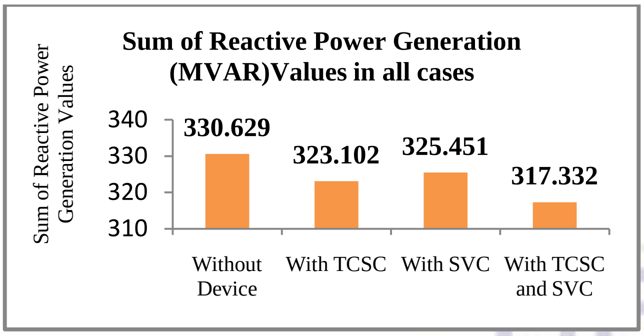

Figure 10: Sum of Reactive power generation values in all Cases

In case 2 the total real power loss and reactive power generation are reduced by 1.743 MW and 5.178 MVAR respectively. The percentages of reduction are 2.33% and 1.57% respectively.

In case 3 the total real power loss and reactive power generation are reduced by 3.385 MW and 13.297 MVAR respectively. The percentages of reduction are 4.52% and 4.02% respectively.

V. CONCLUSIONS

Installation of TCSC and SVC devices in a power system improves the system voltage stability limit under line outage contingencies. Nevertheless, the benefits of TCSC and SVC devices greatly depend on where the devices are located. Contingency condition is taken for voltage stability improvement as voltage instability is triggered mostly by line outages. In this work, the application of TCSC and SVC devices to improve the voltage stability limit under most critical line outage contingency condition is discussed. The proposed method finds the most suitable locations to install TCSC and SVC for improving the system voltage stability limit by reducing the losses and supplying reactive power during the most critical line outage. The optimization is done through the PSO algorithm. The algorithm is able to find the optimal solution with a relatively small number of iterations and particles, therefore with a reasonable computational effort.

The simulation carried out on IEEE 30 bus test system validates the effectiveness of this work. The simulation results show that by installing TCSC and SVC controllers at suitable locations, the system can be operated with voltage security even under severe line outages.

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