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Particle Swarm Optimized Voltage Stability Analysis Of IEEE 14 Bus System with SVC and TCSC

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Abstract— Over a last few decade's voltage instability is a concern phenomenon in power industry. The main cause of voltage instability is the deficit of reactive power in the system and the Active Power losses due to increased inductive reactance of transmission line. Flexible AC transmission system (FACTS) devices can improve the line losses by varying inductive reactance there by increasing Active Power in the system and controlling reactive power by Facts devices which tends to control voltage within the specific limit. In this paper the work is proposed with the help of IEEE 14 bus system in Power World Simulator and comparison have been made in MATLAB. The index of voltage stability Fast Voltage Stability Index (FVSI) gives information about the line which is prone to voltage collapse. At last the location and rating of SVC and TCSC are optimized with help of Particle Swarm Optimization Algorithm to get the voltage within a specific range at all the load buses.

Keywords—FACTS devices, Fast voltage stability index, Power World Simulator , SVC, TCSC, Particle Swarm Optimization.

I. INTRODUCTION

The use of Electrical Energy is rapidly increasing due to fast industrialization and urbanization. Due to this power system runs under stressed condition due to rapidly increasing power demand. The main objective of any power system is to supply power to consumer at minimum cost and too within acceptable frequency and voltage limit. Further the situation become even worse when system is disturbed by critical contingencies like heavy load and transmission line outages. Due to this stresses developed the system have raised concern about voltage instability in power system due to reactive power reserve to the voltage profile.

As India is the country of large population the requirement of power demand increases rapidly. So the existing transmission network requires to carry huge power over the transmission line. Due to these heavily loaded line there will be deficit of reactive power in the line which is one of the major factor of voltage instability. The voltage stability phenomenon is characterized by progressive drop in voltage which occurs mainly because of inability of network to meet increasing demand of reactive power. With increased loading the voltage across the various bus tends to decreases and reactive power losses increases which leads to voltage collapse in the power system.

So Voltage Stability is the ability of the power system to maintain constant voltage at all bus in the power system after being subject to disturbances [1]. Voltage Instability is the local phenomenon where load voltage gets fluctuated when there is a deficit of reactive power on that bus [2-3]. So for avoiding these drawbacks conventional controllers such as Transformer Tap Changer, Phase Shifter are commonly used for improving voltage instability [4-5]. But these controllers are very slow in response and have many limitations. So for avoiding slow response phenomenon the fast acting Flexible Transmission System (FACTS) devices has been implemented which gives faster responses and enhance voltage stability.

FACTS controller are the devices which uses advanced power electronics controller which controls their characteristics just by controlling the firing angle and regulate the control of active power and reactive power through the line and improves voltage stability [5-6]. Various FACTS devices like Static VAR Compensator (SVC), Static Synchronous Compensator (SSSC), Thyristor Controlled Series Compensator, Unified Power Flow Controller (UPFC) etc. Placement of these devices at a particular location improves line flows and reactive power losses in the line which improves voltage stability [7-15].

The best method to develop a weakest bus in the power system for that various stability index has been proposed like modal matrix, Fast Voltage Stability index (FVSI), Line Stability Index (LSI), New Voltage Stability Index (NVSI) these index gives the range of values for which one can determine which bus in the system is prone to voltage collapse [16-17]. Based on these index Fast Voltage Stability Index(FVSI) is simple accurate and gives better results.

Various Optimization techniques such as Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO) etc. are computational techniques that optimized problems by iteratively trying to improve candidate's position and moving these particles in search space according to simple mathematical formula by varying particle position and velocity. Here for voltage stability PSO is implement for placement for SVC and TCSC [18-23].

So this paper is followed by Section I which contains the introduction of how large loading of active and reactive power effect the voltage stability. Section II describes various methodology with consideration of FACTS devices and its necessity technical description with Fast voltage stability index mathematical formulation and basics of Particle Swarm Optimization. Section III describes the result and discussion of simulation of IEEE 14 bus system with comparison with MATLAB and placement of various Facts devices with conventional as well as intelligence techniques.

II. PROPOSED METHODOLOGY

A. Facts Devices

FACTS devices in turns used to provide reactive power compensation and improve power flow in transmission line which improves voltage stability margin and reduce line losses. Here in this paper Facts devices for implementation of voltage stability taken into consideration are SVC and TCSC.

1. Static VAR Compensator

SVC is a parallel or a shunt connected compensator or a controller whose output is controlled to exchange capacitive or inductive current and used to control reactive power in the network [3].

SVC comprises of Thyristor Switch Reactor (TSC) for absorbing the reactive power and Thyristor switch Capacitor (TSC) for supplying reactive power. So it is a device which can operate in inductive mode as well as capacitive mode of operation by varying the firing angle (α) [8-9].

The TCR comprises of fixed reactor of inductance L and bidirectional thyristor value which are fixed with a voltage range of 90º to 180º within voltage stability control.
With the help of TCR and TSC reactive power at the bus can vary continuously to maintain constant voltage and transmission power flow in transmission network either in disturbance or in normal operating condition shown in fig 1 and fig 2 [10-11].
The TCR at the fundamental frequency are considered to be a variable reactance given by

$$\boldsymbol{X_v = X_L \frac{\pi}{2(\pi-\alpha)+sin2\alpha}} \quad (1)$$

Where $X_L$the reactance is caused by the fundamental frequency without thyristor and α is the firing angle.

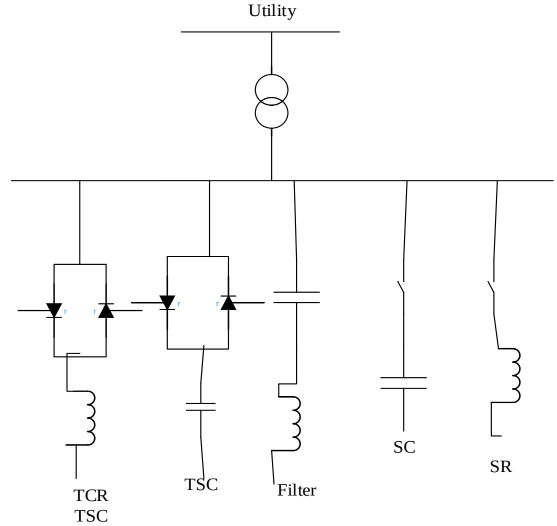

Figure 1 Basic Utility of SVC

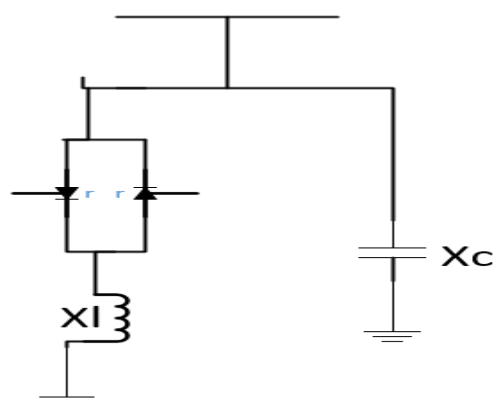

Figure 2. Basic Structure of SVC

2. Thyristor controlled Series Compensation (TCSC)

TCSC is a type of series compensator which control the line power flow by compensating series inductive reactance and reducing it thereby increasing line power transfer capability which in turns increases the voltage at that buses.

TCSC also provides many benefits like system power damping oscillation and system sub-synchronous resonance. TCSC is a capacitive reactance compensator which contains series capacitor in parallel with TCR (Thyristor controlled reactor) in order to provide smoothly variable series capacitive reactance. As TCSC is connected between transmission line between I and k bus where the reactance of TCSC is a function of firing angle α of TCR.TCSC can controlled to work in either capacitive or inductive mode of operation. TCSC can work in bypassed mode, Blocked mode and Vernier mode of operation just by varying the angleα depicted in fig 3 and fig4.

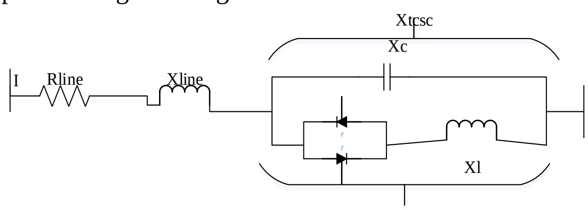

Figure 3 Basic Structure of TCSC

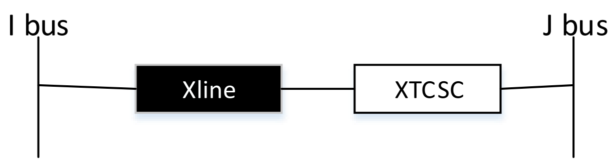

Figure 4 Equivalent Circuit of TCSC

$$\boldsymbol{Z_{ij} = Z_{line} + Z_{TCSC}} \tag{2}$$
$$\boldsymbol{Z_{TCSC} = -jX_{TCSC}} \tag{3}$$
$$\boldsymbol{X_{TCSC} = (1 - K)X_{line}} \tag{4}$$

Where K= degree of compensation. So if the reactance of line is 0.5144 50 % degree compensation would increase the power transfer up to two times. Compensation should be in the range of -0.7 Xline to 0.2 Xline.100% compensation should be avoided which results in series resonance. Practically 50 % to 70 % percent are generally chosen for line reactive compensation [13-15].

B. Stability Index

There is various stability index proposed by various researcher's line stability index (Lmn), V/V0 index, Fast voltage stability index(FVSI), are known index which gives information about which line or bus in the power system are prone to voltage collapse. In power system stability index are calculated for two purposes to know a) which is the critical bus or line in the power system b) how much a system is close to stability limit. Here Fast voltage stability index is proposed which gives information about line which prone to collapse and the bus connected to it. As FVSI is derived from Line voltage stability index it is less calculative and converges faster as compared to other stability index.

1. Fast Voltage Stability Index

FVSI is used for the prediction of the behaviour of voltage collapse and contingencies analysis caused by line outages in power system [16]. It is a simple and reliable mathematical formulation which gives the index value closed to 1 if the line is considered to be the critical line and bus connected to the line are considered to be a critical bus. FVSI is sorted out at every line the highest FVSI gives most critical outages in the system. FVSI provides indicative tool for voltage collapse and ranking the contingencies as well as it also possible to implement practically [17].

Consider a two load bus system shown in fig 5 where power is flowing from bus 1 to bus 2 where current incorporated the direction of flow.

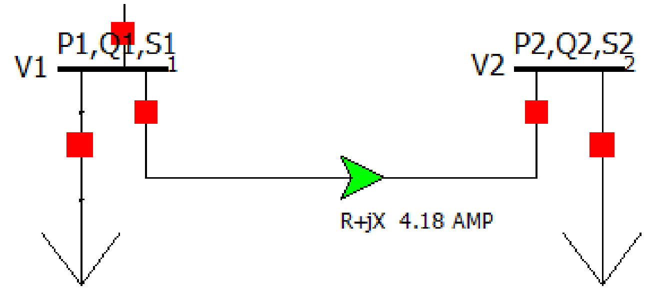

Figure 5 Two bus system with receiving and sending end parameters

V1, V2 = Voltage on sending and receiving end buses.
P1, Q1 = Active and Reactive power on sending bus
P2Q2 = Active and reactive power on receiving end bus.
S1, S2 = Apparent Power on Sending and receiving end bus
δ = angle difference between seding and receiving end bus
Let

$$\mathbf{I = \frac{V1\angle 0 - V2\angle\delta}{R + jX}} \tag{5}$$

Apparent power at bus 2 is given by

$$\mathbf{S_2 = V_2 I^*} \tag{6}$$

So I would be written as

$$\mathbf{I = \frac{S2}{V2} = \frac{P2 - jQ2}{V2\angle -\delta}} \tag{7}$$

Multiplying the above terms, we get

$$\mathbf{\frac{V1\angle 0 - V2\angle\delta}{R + jX} = \frac{P2 - jQ2}{V2\angle -\delta}}$$

So

$$\mathbf{V1V2\angle - \delta - V2^2\angle 0 = (R + jX)(P2 - jQ2)} \tag{8}$$
$$\mathbf{V1V2\cos\delta - V_2^2 = RP_2 + XQ_2} \tag{9}$$

Rearranging both terms we get

$$\mathbf{\left[\frac{R}{X}\sin\delta + \cos\delta\, V_1\right]^2 - 4\left[X + \frac{R^2}{X}\right] Q_2 \geq 0} \tag{10}$$

So the equation became

$$\frac{\mathbf{4Z^2Q_2X}}{\mathbf{V_r^2(Rsin\delta+Xcos\delta)}} \leq \mathbf{1} \tag{11}$$

δ is very small then

$$\boldsymbol{\delta = 0} \qquad \boldsymbol{Rsin\delta = 0} \qquad \mathbf{Xcos\delta=X}$$

Therefore, for the two bus system FVSI can be defined as

$$\mathbf{FVSI_{12}} = \frac{\mathbf{4Z^2Q_L}}{\mathbf{V_i^2X}} \tag{12}$$

Where
Z= line impedance
X= line reactance
Q_l =Reactive power at receiving end
V_i =Receiving end voltage

If the value of FVSI that is evaluated close to 1 indicates that particular line is closed to the instability point which may leads to voltage collapse in the entire system.

C. Particle Swarm Optimization

Particle Swarm Optimization (PSO) is a computational method that optimizes a problem by iteratively trying to improve a candidate solution with regard to a given measure of best quality [18]. It solves problem by population iteration method of candidate solution and moving these particles around in the search space according to simple mathematical formulae over the particles position and velocity [19-20]. Each particles movement is influenced by its local position but it is also guided toward the best known position in search space which are updated a better position guided by other particles [21-22]. All particle fly in the search space to explore optimal solution. Each particle update its position based upon its own best position among particles and its previous velocity vector according to the equation.

$$\mathbf{V_i^{k+1} = wV_i^k + c_1r_1^k\left[Pbest_i^k - x_i^k\right] + c_2r_2^k\left[gbest_i^k - x_i^k\right]} \tag{13}$$

$$\mathbf{x_i^{k+1}} = |\, \mathbf{x_i^k + V_i^{k+1}} | \tag{14}$$

$$\mathbf{w = w_{max} - {}^{w_{max} - w_{min}}/_{iter_{max}} * iter} \tag{15}$$

V_i^k= Current Velocity of particles i at iteration k
V_i^{k+1}= Current Velocity of particles I at iteration k+1
$\boldsymbol{x_i^k}$= Current position of particles i at iteration k
x_i^{k+1}= Current position of particles I at iteration k+1
w_{max} = initial weight or inertia weight at beginning of iteration
w_{min}= final weight or inertia weight at the end of the iteration
$iter_{max}$= maximum iteration number
$iter$ = Current iteration number

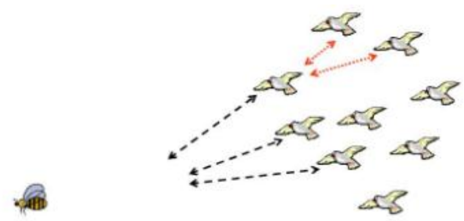

Figure 6 Particle Food Search

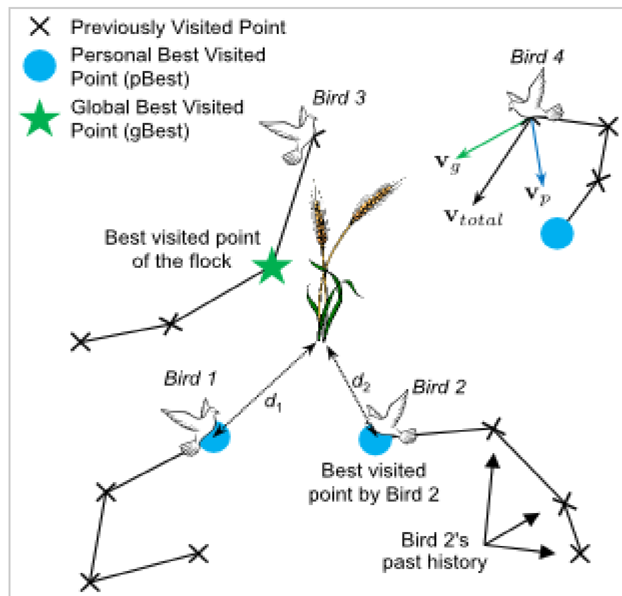

Figure 7 Basics of Particle Swarm Optimization

Figure 6 and 7 shows the basics of PSO the particles are in search for food denoted by cross when one particle knows the food they try to communicates with the other birds and try to update their position finding the personal best value denoted by blue dot. At last the particle further communicate with each other and iteratively update their position for finding food which is known as global best value.

Constant C_1 is called a self- confidence range, and C_2 is called swarm range. Both co efficient pulls particles to pbest and gbest location. Low value of acceleration coefficient allows particles to roam far away from global position and high value pulls the particle to previous best value. The term $C_1r_1^k\left[pbesti^k - x_i^k\right]$ is called particle "memory influence" or "Cognition part" which represent private thinking of particles itself and term $C_2r_2^k\left[gbesti^k - x_i^k\right]$ is called "Swarm influence or Social part" which represent collaboration among particles.

III. RESULTS AND DISCUSSION

A. IEEE 14 Bus System

IEEE 14 Bus System Consists of 3 Generators buses (PV bus), 11 load buses (PQ bus), 20 Transmission lines with Generation of 273.3 MW and 107.2 MVAR and Demand of 259.3 MW and 73.6 MVAR and the losses is 14.4 MW and 33.6 MVAR respectively. The location of SVC and TCSC are placed with the help of conventional method. The main objective is to minimize MW and MVAR losses to enhance the voltage stability by proper placement of FACTS devices. IEEE data is taken from Standard IEEE 14 bus test system shown in fig 8 [23].

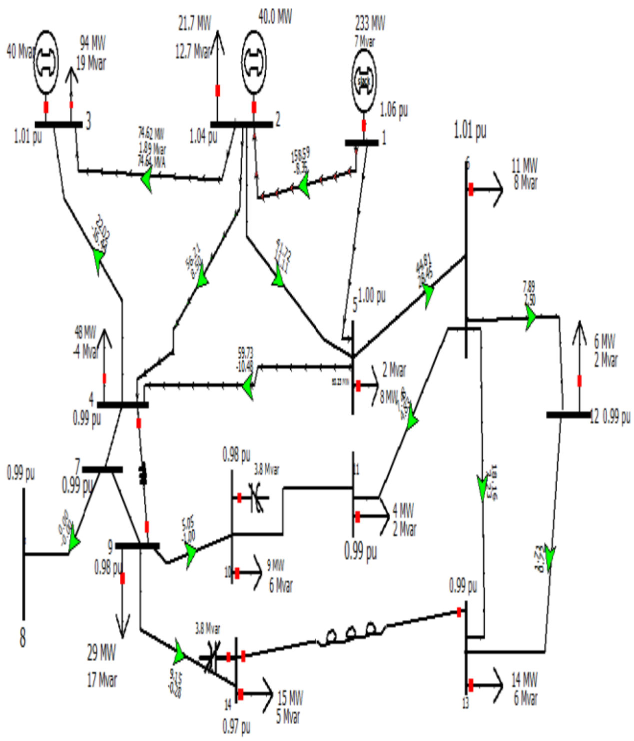

Figure 8 IEEE 14 bus system with Conventional Method

B. Voltage Stability Comparison of base case in Power World (No Compensation)

The voltage stability comparison has been with base case that is when no compensation is attached to the system.

Table 1 Power world comparison with base case

BUS	Voltage(specified)	Voltage(PU)
1	1.06	1.06
2	1.045	1.034
3	1.01	0.982
4	1	0.987
5	1	0.989
6	1	0.961
7	1	0.987
8	1	0.98
9	1	0.961
10	1	0.957
11	1	0.969
12	1	0.972
13	1	0.965
14	1	0.943

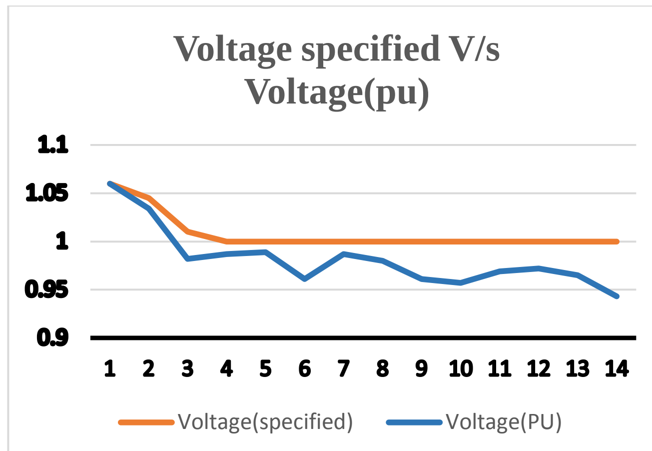

Figure 9 Comparison with voltage specified and voltage with base case

Table 1 and figure 9 shows the comparative analysis of power world with base case where one can see that without any compensating devices in the system the voltage is reducing that what it is specified. Further with the increase in active and reactive power loading the voltage collapse more which leads to voltage instability.

C. Software comparison of voltage stability with power world and MATLAB

Comparison analysis have been made for voltage stability in power world as well as in MATLAB with the help of newton Raphson method. The results show for voltage as well for losses gives same result as power world. So we can consider power world Simulator as a base software for over analysis purpose.

Table 2 Comparison with power world and MATLAB

Bus	Voltage pu (Power World)(0.144 pu losses)	Voltage(MATLAB)(0.15 pu losses)
1	1.06	1.06
2	1.034	1.04
3	1	1.01

4	0.982	1.02
5	0.987	1.03
6	0.989	1
7	0.975	1
8	0.961	1
9	0.957	0.981
10	0.969	0.982
11	0.969	1.001
12	0.972	1.01
13	0.965	1
14	0.943	0.971

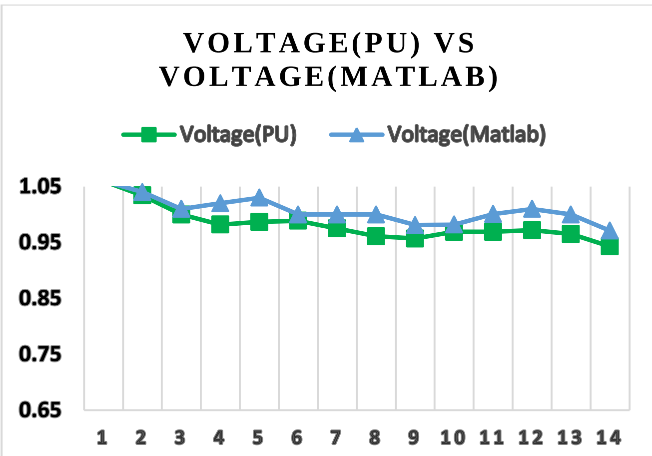

Figure 10 Comparison graph with Power world and MATLAB

Table 2 and figure 10 shows that the active power losses in Power world is 0.144 pu and in MATLAB is 0.15 pu which is approximately same. So we can consider power world as our base software for Voltage Stability.

D. Voltage Stability Comparison with connecting FACTS Devices (Conventional Method).

1. Voltage Stability when SVC of 4 MVAR each are connected at Bus 14 and 10 with switching nominal MVAR from -10 to 10 with target value of 1 pu

Table 3 When SVC is placed into the system

Load Bus	Voltage Specified	Voltage without SVC	Voltage with SVC
2	1.045	1.034	1.0378
3	1.01	1	1
4	1	0.982	0.991
5	1	0.987	0.995
6	1	0.989	1
9	1	0.961	0.981
10	1	0.957	0.98
11	1	0.969	0.989
12	1	0.972	0.99
13	1	0.965	0.985
14	1	0.943	0.969

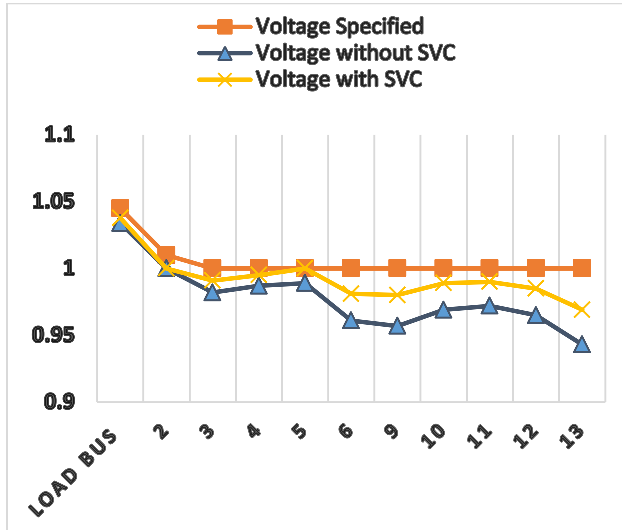

Figure 11 Comparison graph with and without SVC

SVC is placed on that bus which has low voltage that is bus 14 and bus 10 indicated in Table 2. The comparison analysis has been made in Table 3 which shows that the voltage profile improves when SVC is connected in the system which is represent in fig 11.

2. Voltage Stability when TCSC of 50 % Compensation is connected at line 4-9 and 13-14.

Table 4 Voltage Stability comparison with and without TCSC

Load Bus	Voltage Specified	Voltage without TCSC	Voltage with TCSC
2	1.045	1.034	1.032
3	1.01	1	1
4	1	0.982	0.982
5	1	0.987	0.989
6	1	0.989	0.991
9	1	0.961	0.98
10	1	0.957	0.97
11	1	0.969	0.981
12	1	0.972	0.982
13	1	0.965	0.971
14	1	0.943	0.95

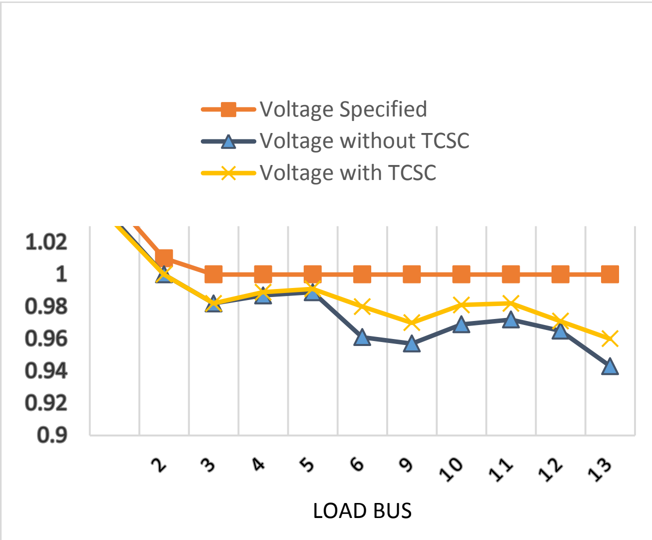

Figure 12 Voltage comparison with and without TCSC

TCSC is placed in the system where the inductive reactance of line is greater that is line 4-9 and 13-14. Table 4 shows the comparative analysis with and without TCSC. Also figure 12 depicts the comparative analysis in graph form.

3. Voltage Stability when both SVC and TCSC are connected in the System.

Comparison analysis has also made when both SVC and TCSC are placed in the system. SVC is place on bus 14 and 10 and TCSC are placed on line 4-9 and 13-14 which depicts the conventional method of analysis of voltage stability rather than optimized method. With connection of both FACTS Devices the voltage profile improves gradually which is depicts in Fig 13

Table 5 Voltage Stability Comparison with and without FACTS Devices with conventional method

Load Bus	Voltage Specified	Voltage without TCSC and SVC	Voltage with TCSC and SVC
2	1.045	1.034	1.032
3	1.01	1	1
4	1	0.982	0.992
5	1	0.987	0.996
6	1	0.989	1.004
9	1	0.961	0.991
10	1	0.957	0.9785
11	1	0.969	0.987
12	1	0.972	0.988
13	1	0.965	0.982
14	1	0.943	0.971

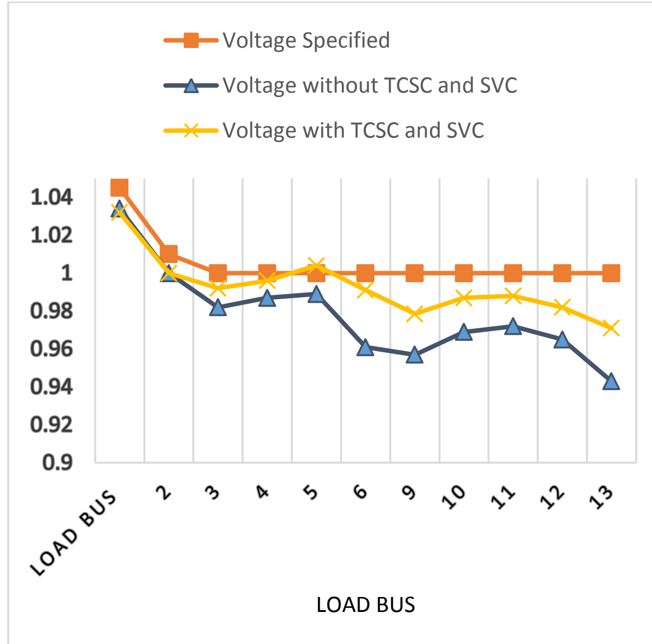

Figure 13 Voltage Comparison with and Without FACTS Devices

The basis of comparison is made with conventional techniques which can be identified by low voltage of the bus and increased transmission line inductive reactance for placement of SVC and TCSC respectively. The following conventional techniques will be compared with optimized technique using PSO in the above section.

E. Fast Voltage Stability Index(FVSI)

Fast Voltage stability index give information about which transmission line is prone to more voltage collapse. If the index is approaching 0 then it is considered to be voltage stable but when it is approaching to 1 then the line is more voltage instable. So based upon this FVSI has been calculated for every transmission line and ranking has been given for the same.

Table 6 FVSI Index for 20 Transmission lines

Line No	Branch	FVSI	Rank
1	1_2	0.04077	11
2	1_5	0.114	3
3	2_3	0.02509	13
4	2_4	0.0863	6
5	2_5	0.1089	5
6	3_4	0.1639	2
7	4_5	0.017	16

8	4_7	0.0139	17
9	4_9	0.112	4
10	5_6	0.278	1
11	6_11	0.0115	18
12	6_12	0.037	12
13	6_13	0.0605	9
14	7_8	0	20
15	7_9	0.07089	8
16	9_10	0.0039	19
17	9_14	0.0195	15
18	10_11	0.048	10
19	12_13	0.0223	14
20	13_14	0.0719	7

From the Table 6 we can see that the line 5-6 is more prone to voltage collapse as it is approaching more to voltage instability. Further the ranking has been given to all transmission line according to their approaching towards voltage instability. Fig 14 shows the comparison with FVSI and transmission branch.

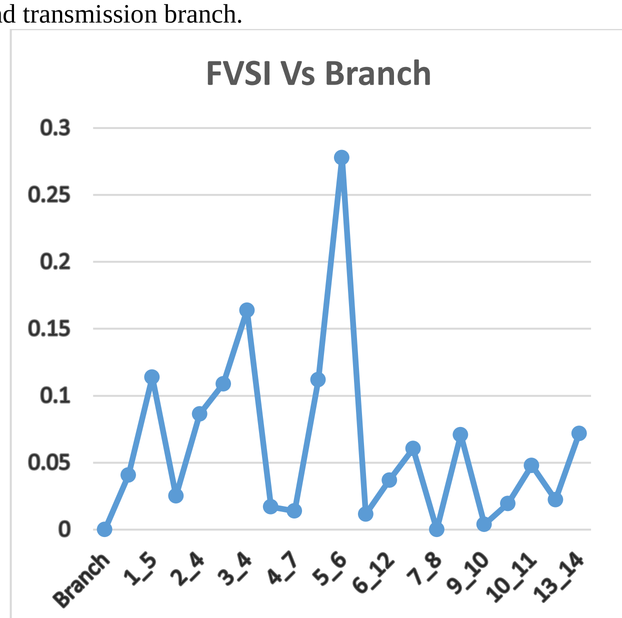

Figure 14 Comparison of FVSI V/s Branch

1. Fast Voltage Stability Index (FVSI) with loading as well as Facts Devices.

Table 7 FVSI comparison with loading as well as FACTS device

Line	Base Case	10%	20%	30%	TCSC	SVC	SVC and TCSC
5_6	0.278	0.318	0.363	0.429	0.269	0.222	0.2156
3_4	0.1639	0.184	0.2138	0.241	0.152	0.1399	0.1283
1_5	0.114	0.131	0.1496	0.169	0.108	0.0693	0.0636
4_9	0.112	0.129	0.1509	0.167	0.04	0.0467	0.0154
2_5	0.108	0.113	0.1201	0.132	0.088	0.0847	0.07

From Table 7 five Critical line based upon FVSI are considered and based upon this loading with 10 %, 20 % and 30 % contingencies are taken with also the placement of SVC, TCSC and both SVC and TCSC. Further we can see that FVSI approaches to zero when combination of FACTS devices is connected in the system. So rather than one facts devices two different devices should be connected in the system for voltage profile enhancement which is depicted in graph form in figure 15.

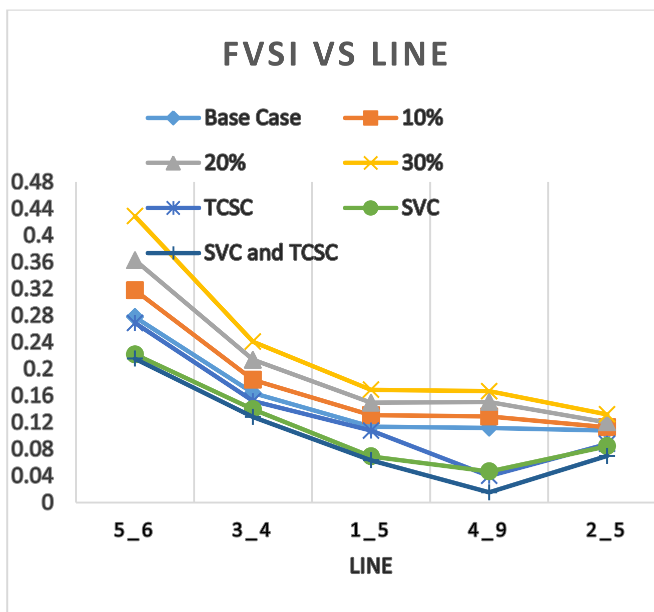

Figure 15 Comparison with line FVSI with line loading

F. Particle Swarm Optimization for placement of SVC

1. Objective Function for SVC

$$F_x = min(F_1, F_2) \quad (16)$$

$$F_1 = FVSI \quad F_2 = Q_{loss} \quad (17)$$

$$\text{FVSI} = \frac{4Z^2 Q_L}{V_j^2 X} \quad (18)$$

$$\text{Qloss} = \sum_{i=1}^{NB} gij \; (V_j^2 - V_i^2 + 2V_i V_j \, co(\delta_i - \delta_j)$$

Equality Constraint

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

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

Inequality Constraint

$$Qloss_{min} \le Qloss \le Qloss_{max}$$

$$V_i^{min} \le V_i \le V_i^{max}$$

SVC -100 MVAR ≤ Q_{SVC} ≤ 100 MVAR

2. Trial and Error PSO optimization for decreasing FVSI in line considering objective function

Table 8 Optimization for decreasing FVSI

Bus	Line 5-6	Line 3-4	Line 1-5	Line 4-9	Line 2-5	Rank
4 (1 MVAR)	0.272	0.1552	0.101	0.1105	0.1026	8
5 (1 MVAR)	0.277	0.234	0.11	0.11	0.106	9
6 (4 MVAR)	0.241	0.145	0.0975	0.097	0.099	1
9 (8.3 MVAR)	0.244	0.232	0.081	0.054	0.092	2
10 (2.9 MVAR)	0.262	0.243	0.102	0.092	0.102	4
11 (1 MVAR)	0.262	0.234	0.102	0.092	0.102	4
12 (1 MVAR)	0.266	0.223	0.11	0.108	0.106	7
13 (2.9 MVAR)	0.255	0.245	0.102	0.098	0.102	3
14(2.5 MVAR)	0.262	0.242	0.092	0.098	0.107	4

Table 8 depicts the placement of SVC by trial and error method by connecting SVC on every bus in the system for five critical FVSI line. The ranking is greater on bus 6 and bus 9. So placement for SVC with 50 % compensation is considered for optimal location with reference to FVSI.

3. Optimized PSO for decreasing Qloss in line.

Table 9 Optimized PSO for Qloss in the line

Bus	Qloss 5-6	Qloss 3-4	Qloss 1-5	Qloss 4-9	Qloss 2-5	Rank
4 (1 MVAR)	7.18	1.96	18.97	1.61	18.97	9
5 (1 MVAR)	7.18	1.95	18.91	1.61	18.91	8
6 (4 MVAR)	6.78	1.95	17.4	1.54	0.32	2

9 (8.3 MVAR)	6.59	0.83	15.64	1.48	0.42	1
10 (2.9 MVAR)	6.82	1.09	15.65	1.48	0.42	3
11 (1 MVAR)	7.1	1.96	18.88	1.6	0.25	7
12 (1 MVAR)	7.09	1.96	18.88	1.6	0.2	6
13 (2.9 MVAR)	6.89	1.99	17.94	1.56	0.3	4
14 (2.5 MVAR)	6.98	1.98	18.23	1.57	0.24	5

From the above Table 9 it shows that Qloss in the bus 6 and 9 are very less compared to the other bus. Here SVC is placed with 50 % compensation on every bus and the critical bus are identified by trial and error method.

4. Optimized PSO Parameters

Table 10 Optimized PSO Parameters

Correction Factor	2
Gbest	38
i	49
j	7
index	50
inertia	1
Swarm size	49
Iteration	30
X=	10.0005
Y=	10.0007577
Swarm best value so far	1000
Initial Velocity	0

Table 10 shows the parameters initialization with global best value of 39 with swarm size of 49. The sphere function has been evaluated as a standard benchmark function with fitness function of Var=$(x-10)^2+(y-12)^2$ where x= 10.0005 and Y= 10.0007577.

5. PSO Swarm movement for placement of SVC

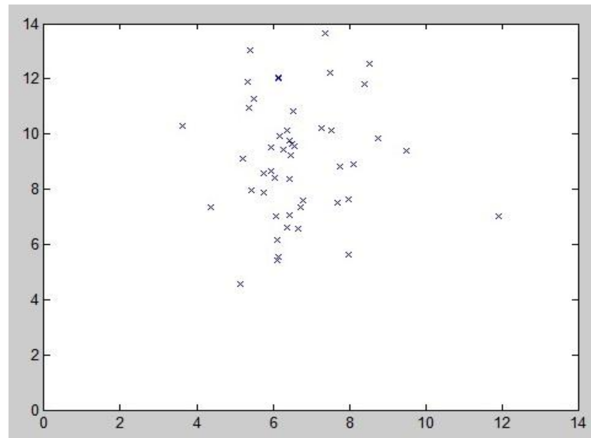

Figure 16 Swarm particles scattered from each other

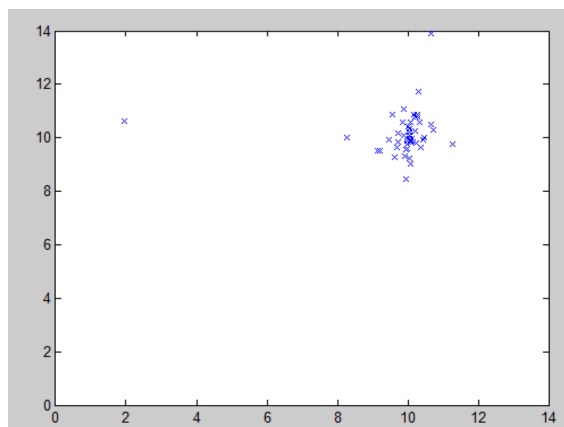

Figure 17 Swarm particle in search space

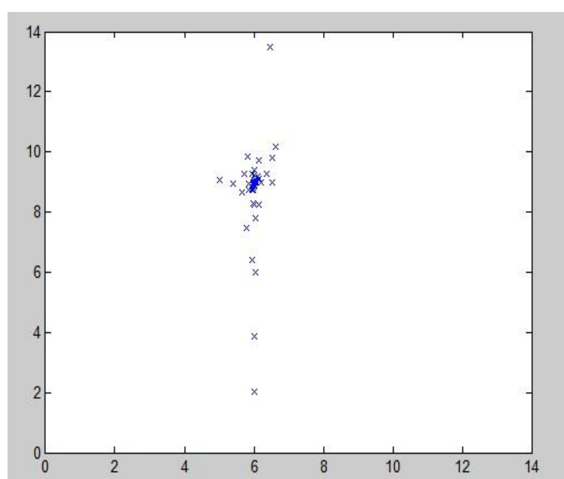

Figure 18 Swarm Particles in search space

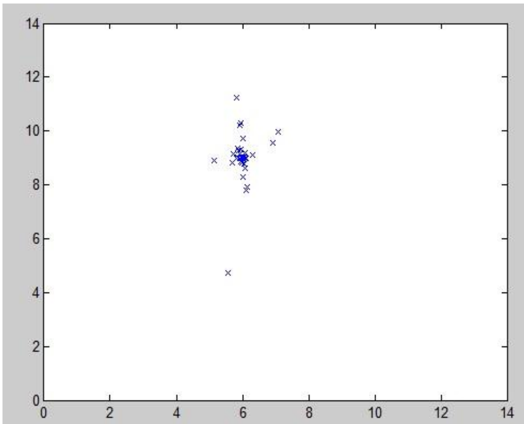

Figure 19 Swarm Particles at its global best value

Figure 16 shows that the particle are scattered separately, but for finding food they communicate with each other by trying to iteratively improves their position and search for global best value as shown in figure 19. This shows that the placement of SVC should be between 6 to 10. But from the minimization function we get 6 and 9 for placement of SVC. So we consider bus 6 and bus 9 for optimal placement of SVC.

6. Comparative analysis with base case, Conventional method (14, 10) and optimized method (6, 9) of 4 MVAR each for placement of SVC.

Table 11 Comparative analysis for placement of SVC

Load Bus	Base Case Voltage (pu)	Conventional method SVC	Optimized Method SVC
2	1.034	1.0378	1.03
3	1	1	1.01
4	0.982	0.991	1
5	0.987	0.995	0.998
6	0.989	1	1.01
9	0.961	0.981	0.983
10	0.957	0.98	0.981
11	0.969	0.989	0.993
12	0.972	0.99	0.995
13	0.965	0.985	0.989
14	0.943	0.969	0.969

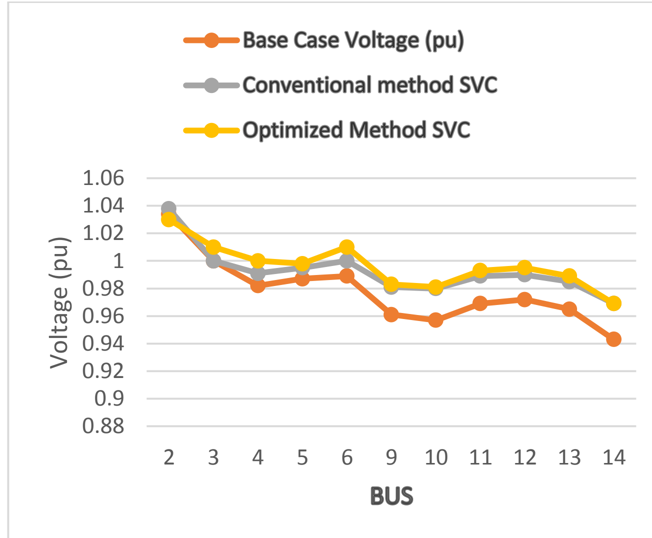

Figure 20 Comparison with Conventional and Optimized method

For conventional method the placement for SVC are bus 14 and bus 10. But in optimized method the placement of SVC is bus 6 and bus 9 which is indicated by yellow line in fig 20. So we can say that optimized method is best for voltage stability enhancement.

G. Particle Swarm Optimization for placement of TCSC

1. Objective function for TCSC

$$F_x = min(F_1, F_2) \quad (19)$$

$$F_1 = FVSI \quad F_2 = P_{loss} \quad (20)$$

$$\text{FVSI} = \frac{4Z^2 Q_L}{V_j^2 X} \quad (21)$$

$$\text{Ploss} = \sum_{i=1}^{Nl} gij\ (V_i^2 + V_j^2 - 2V_i V_j \cos(\delta i - \delta j))$$

Equality Constraint

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

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

Inequality Constraint

$$Ploss_{min} \le Ploss \le Ploss_{max}$$

$$V_i^{min} \le V_i \le V_i^{max}$$

TCSC -0.8 Xline ≤ Xtcsc ≤ 0.2 Xline

2. Placement of TCSC for 50 % compensation in each line

Table 12 Individual Placement of TCSC in each branch

Line No	Branch	FVSI	Rank
1	1_2	0.11918	13

2	1_5	0.064	9
3	2_3	0.0538	7
4	2_4	0.1938	16
5	2_5	0.0594	8
6	3_4	0.13916	14
7	4_5	0.59736	19
8	4_7	0.483	18
9	4_9	0.086	11
10	5_6	0.152	15
11	6_11	0.0354	4
12	6_12	0.0225	3
13	6_13	0.05025	5
14	7_8	0	1
15	7_9	0.3602	17
16	9_10	0.0024	2
17	9_14	0.1143	12
18	10_11	0.692	20
19	12_13	0.0511	6
20	13_14	0.0657	10

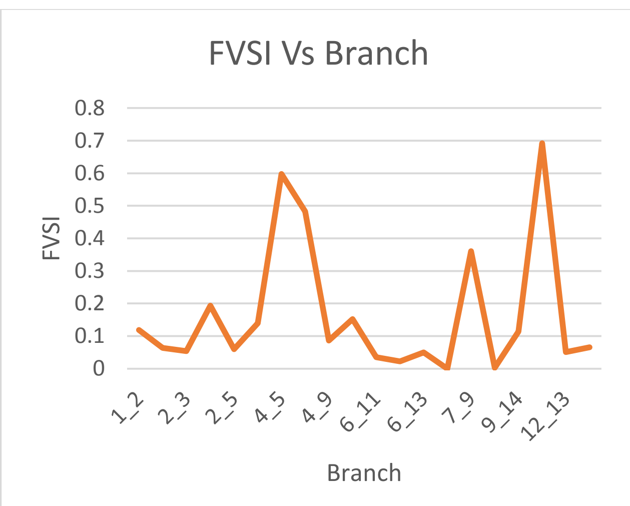

Figure 21 FVSI V/s Branch for individual placement for TCSC

From Table 12 we can say that the FVSI is smaller in Transmission line branch 6-12 and 9-10 so we consider these branch as optimal placement for TCSC. Figure 21 shows FVSI V/s branch where we can see that the line 12 and 16 are very much low compare to other branch.

3. Power Flow with and without TCSC

Table 13 Power Flow with and without TCSC

Line No	Branch	Power Flow Before TCSC	Power Flow After TCSC	Percentage Increases
1	1_2	159.04	171.71	12.67
2	1_5	62.51	74.69	12.18
3	2_3	74.82	89.25	14.43
4	2_4	56.4	80.15	23.75
5	2_5	31.88	60.93	29.05
6	3_4	25.57	25.9	0.79
7	4_5	61.1	64.8	3.7
8	4_7	28.64	33.83	5.19
9	4_9	15.6	24.73	9.13
10	5_6	41.94	54.97	13.03
11	6_11	7.72	8.1	0.97
12	6_12	8.03	9.71	0.72
13	6_13	16.88	19.84	2.96
14	7_8	0	0	0
15	7_9	27.69	21.64	6.05
16	9_10	4.92	5.19	0.27
17	9_14	8.72	9.95	1.23
18	10_11	4.65	5.45	0.8
19	12_13	3.23	3.72	0.49
20	13_14	4.93	6.33	1.4

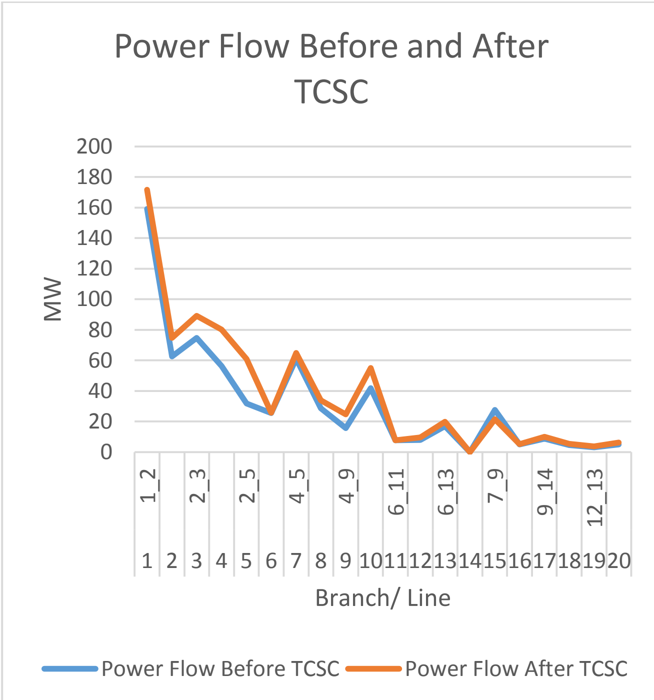

Figure 22 Power flow before and after TCSC

From Table 13 the power flow comparison is made with and without TCSC such that there is small percentage increase in line 6-12 and 9-10. So we consider 6-12 and 9-10 as optimal placement for TCSC.

4. Particle Swarm Parameters for TCSC results

Table 14 PSO parameters for TCSC

Correction Factor	2
Gbest	47
i	49
j	7
index	50
inertia	1
Swarm size	49
Iteration	30
X=	9.99
Y=	11.9941
Swarm best value so far	1000
Initial Velocity	0

Table 14 shows the parameters initialization with global best value of 47 with swarm size of 49. The sphere function has been evaluated as a standard benchmark function with fitness function of Var=$(x-9)^2+(y-10)^2$ where x=9.99and Y= 11.9941.

5. Particle Swarm movement for TCSC

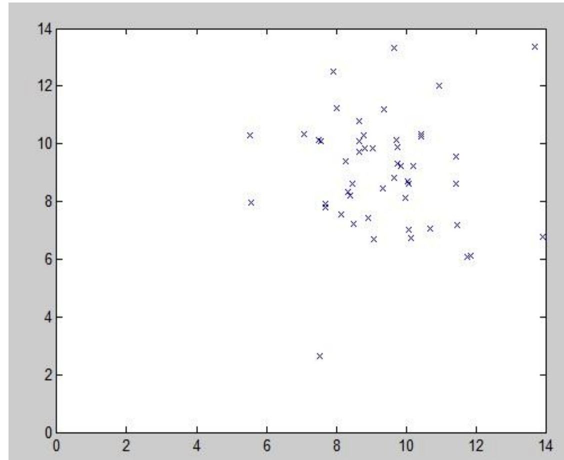

Figure 23 Swarm Particles Scattered from each other's

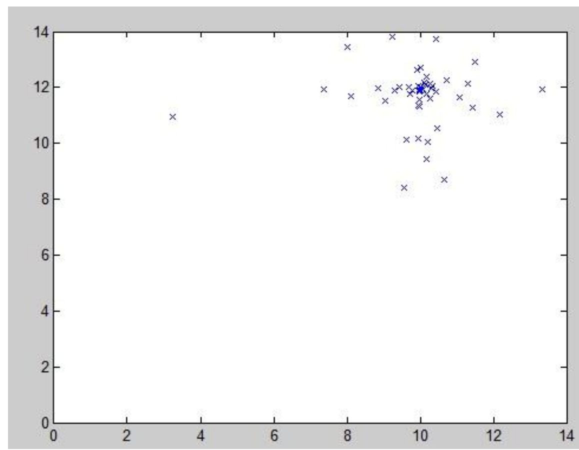

Figure 24 Swarm Particles in search space

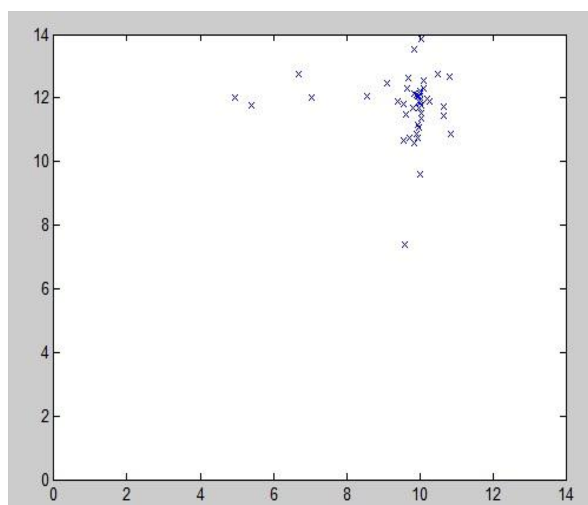

Figure 25 Swarm Particles in search space

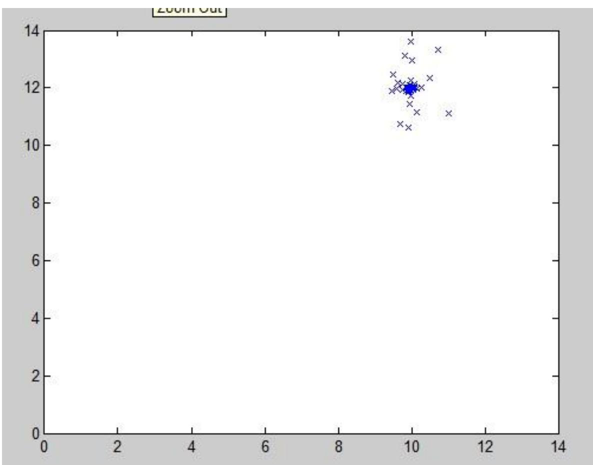

Figure 26 Swarm Particles at its global best value

Fig 23-26shows that the particles are scattered and by communication they try to find global best value. So by placement of TCSC particles try to settle between 9 to 12. So we can consider 9-10 and 6-12 branch as global best value for placement of TCSC.

6. Comparative analysis with base case, Conventional method (4-9,13-14) and optimized method (9-10,6-12) for TCSC Voltage Stability.

Table 15 Conventional and Optimized Method comparison for TCSC

Load Bus	Base Case Voltage (pu)	Conventional method(TCSC)	Optimized Method (TCSC)
2	1.034	1.032	1.034
3	1	1	1
4	0.982	0.982	0.982
5	0.987	0.989	0.987
6	0.989	0.991	0.952
9	0.961	0.98	0.972
10	0.957	0.97	0.965
11	0.969	0.981	0.971
12	0.972	0.982	0.97
13	0.965	0.971	0.96
14	0.943	0.95	0.942

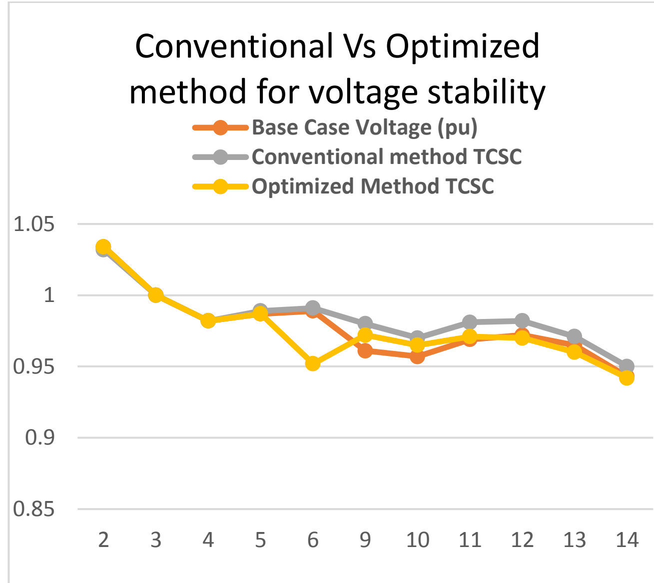

Figure 27 Graph comparison with conventional and optimized method

From Table 15 we can say that with Placement of TCSC there is slightly increase in voltage but power flow in line increases rapidly due to this FVSI approaches to zero these leads to voltage stable system.

H. Optimized Voltage stability for placement for both SVC and TCSC in the system

Table 16 Comparison of voltage stability with conventional and optimized method

Load Bus	Voltage Specified	Voltage without TCSC and SVC	Voltage with Conventional Method	Voltage with optimized method
2	1.045	1.034	1.032	1.04
3	1.01	1	1	1.01
4	1	0.982	0.992	0.998
5	1	0.987	0.996	1
6	1	0.989	1.004	1.017
9	1	0.961	0.991	0.987
10	1	0.957	0.9785	0.9857
11	1	0.969	0.987	0.9977
12	1	0.972	0.988	1
13	1	0.965	0.982	0.994
14	1	0.943	0.971	0.97169

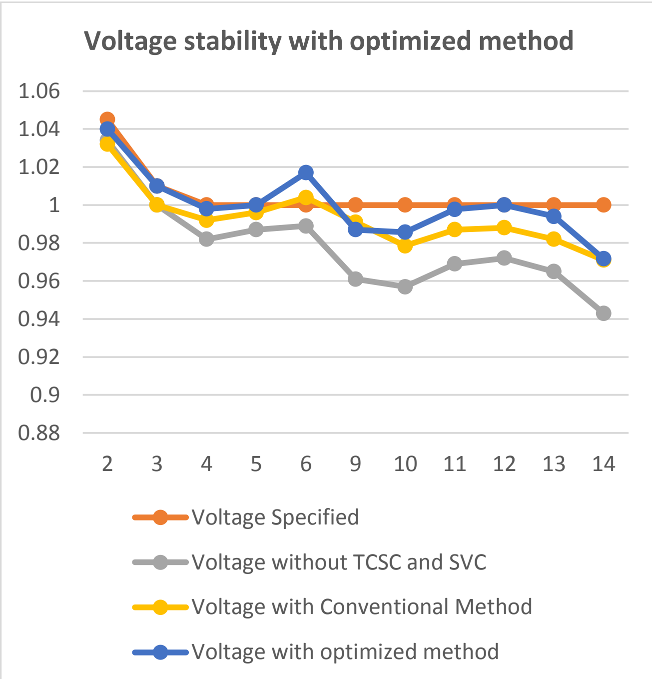

Figure 28 Voltage Stability with optimized method

With Placement of both SVC and TCSC in the system the voltage is approaching to what it is specified. So placement of different FACTS devices should be considered rather that individual devices for improving voltage stability consideration with optimized techniques as shown in table 16.

I. FVSI Comparison with Conventional and optimized method

Table 17 FVSI Comparison with Conventional and optimized method

Line No	Branch	FVSI without SVC and TCSC	FVSI with conventional method	FVSI with optimized method
1	1_2	0.04077	0.039	0.0288
2	1_5	0.114	0.0636	0.0517
3	2_3	0.02509	0.024	0.016
4	2_4	0.0863	0.0799	0.0654
5	2_5	0.1089	0.07	0.0612
6	3_4	0.1639	0.1283	0.1181
7	4_5	0.017	0.011	0.009
8	4_7	0.0139	0.0124	0.0121
9	4_9	0.112	0.0154	0.0144
10	5_6	0.278	0.2156	0.1655
11	6_11	0.0115	0.0102	0.0012
12	6_12	0.037	0.027	0.021
13	6_13	0.0605	0.0546	0.0412
14	7_8	0	0	0
15	7_9	0.07089	0.06891	0.06712
16	9_10	0.0039	0.0031	0.0029
17	9_14	0.0195	0.0192	0.0154
18	10_11	0.048	0.041	0.0405
19	12_13	0.0223	0.0212	0.0199
20	13_14	0.0719	0.07	0.0672

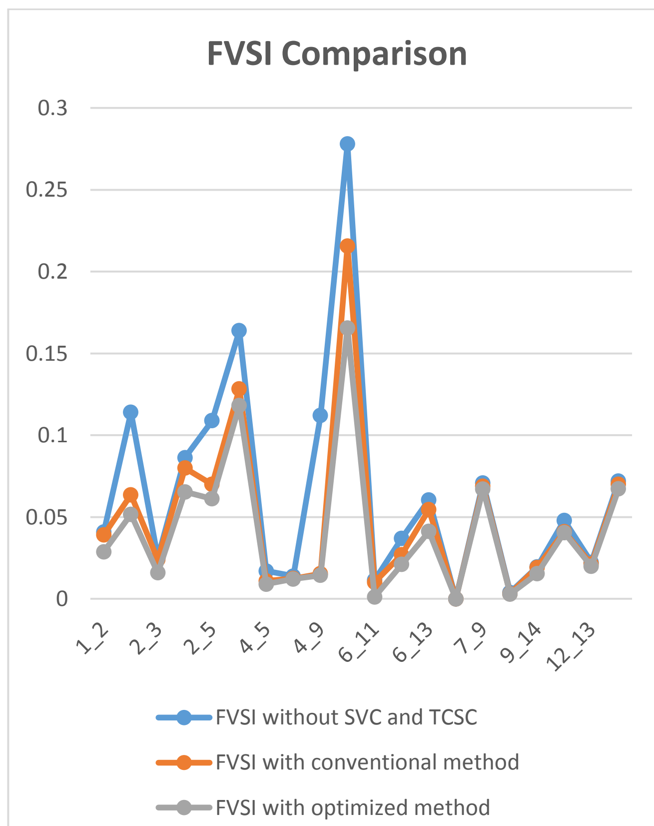

Figure 29 FVSI graph with conventional and optimized method

FVSI comparison has been made without Compensation, with conventional method, and optimized method as shown in Table 17 such that with optimized method the FVSI is approaching more towards zero rather than conventional method. So optimized method is best suitable for voltage stability.

IV. CONCLUSION AND FUTURE SCOPE

For the above Voltage stability improvement, it can be concluded that when we use multiple FACTS devices the voltage stability improves more as compare to single FACTS device connected the voltage in conventional method was 0.97 which has increase to 0.9169 So for placement of Facts devices optimized method is preferred. Further the Fast voltage stability Index (FVSI) which gives information about which line is critical in the system approaches to zero which is indication of voltage stable by connecting two different FACTS devices rather than single device. Also by conventional method the voltage doesn't improves more as compared to optimized method for voltage stability.

The future Scope include connecting different FACTS devices like STATCOM, UPFC etc. and checking for voltage stability improvement.

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[23] Appendix A – Standard IEEE 14 bus System data.

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