A New Approach for Optimal Placement of FACTS Devices in Power System to Mitigate Congestion

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Abstract— **This paper describes a new approach based on particle swarm optimization (PSO) technique for optimal placement of Flexible AC Transmission System (FACTS) device to mitigate congestion. Minimization of real power loss maintaining voltage stability is the objective of the optimization approach. For this study, Static Synchronous compensator (STATCOM) is used as compensation (FACTS) device. The proposed methodology is tested in Modified IEEE 30 bus system and optimization technique's validation is done using external education/research aimed software Power System Analysis Toolbox (PSAT).**

Keywords— **Flexible AC Transmission System (FACTS), Optimal Power Flow Equation (OPF), Particle Swarm Optimization Technique (PSO), Reactive Power, Static Synchronous compensator (STATCOM), Voltage Stability Index (VSI), Power System Analysis Toolbox(PSAT), Congestion Management**

I. INTRODUCTION

ONE of the most important problems facing any power system is voltage stability [1], [2]. A condition where demand for power transmission exceeds system's capacity is called Congestion which causes over-loading of system resulting in cascade outages (black-outs) with uncontrolled loss of load [3], [4]. FACTS device has open a new ways for controlling power as well as bus voltage and increase ability of existing power system due to a rapid improvement in semiconductor technology[5], [6]. FACTS devices also have capabilities to enhance dynamic as well as steady state stability [7]. Reactive power flow could be controlled in the system by generators, synchronous condensers, static compensators, capacitors and tap changing transformers [8].

Minimization of real power loss maintaining system voltage stability is the objective of the optimization approach which is obtained by solving Optimal Power Flow (OPF) problem [9] by using Particle Swarm Optimization (PSO) technique. Unlike other heuristic methods such as ANN and GA, PSO is powerful, easy to understand, easy to implement, computationally efficient and few adjustable parameters [6], [10]. PSO, which is inspired by the social behavior, can handle both continuous and discrete variables.

PSAT is an open source Matlab and GNU/Octave-software package for analysis and design of small to medium size electrical power systems [11].

In this paper, PSO based optimization technique for finding optimal location for placing FACTS device by solving OPF problem for minimum real power loss maintaining voltage stability within limits in given system condition is used. STATCOM is used as FACTS device. The proposed approach is tested in IEEE 30 bus system and optimization technique's validation is done using external education/research aimed software Power System Analysis Toolbox (PSAT).

II. MATERIALS AND METHODS

A. FACTS devices

STATCOM can be both voltage source converter (VSC) and current source converter (CSC) which uses power electronics switches to produce sine wave voltage from a DC source [7], [4]. The STATCOM, through an inductive impedance of low p.u. value, is coupled into the system and has very similar operating characteristics to a synchronous compensator. Like a synchronous compensator a STATCOM compensate any change in system voltage as its natural tendency, even without control action, but its low stores energy means it can do this much more rapidly. The uncertain system planning environment in which today's power system operates means that the advantages of STATCOM technology, in terms of system performance benefits, site area savings and ease of relocation are of increasing value.

The power flow constraints of STATCOM is given by [7]:

$$P_{st} = {V_p}^2 g_{st} - V_p V_{st}(g_{st}\cos(\theta_p - \theta_{st}) + b_{st}\sin(\theta_p - \theta_{st})) \quad (1)$$

$$Q_{st} = -{V_p}^2 b_{st} - V_p V_{st}(g_{st}\sin(\theta_p - \theta_{st}) - b_{st}\cos(\theta_p - \theta_{st}) \quad (2)$$

Where,

-P_{st} and Q_{st} are active and reactive powers supplied by STATCOM to bus respectively.

-V_p is the voltage magnitude of the bus P and V_{st} is the voltage across STATCOM.

-g_{st} and b_{st} are transfer conductance and susceptance between bus and STATCOM respectively.

-Θ_p and Θ_{st} are the voltage angles of bus and STATCOM respectively.

B. Optimal Power flow Solution

The problem of optimizing the performance of the power system network is formulated as a general optimization problem. It is required to state from which aspect the performance of the power system network is optimized.

The optimal power flow problem [9]:

- Aims to minimize loading of system giving maximum system security,
- Aims at minimum operating cost and minimum loses,
- Should be based on operational constraints, and
- Is a static optimization problem with the cost function as a scalar objective function.

Among all the above mentioned condition, we are excluding cost variable and using voltage stability index instead because when we are considering FACTS device cost is basically assumed to be high and our main focus will be providing stable and secure power supply at increased cost.

Above mentioned objective function is subject to following constraints:

$$Min\ P_{loss} = \sum_{i=1, j\in i}^{N_B} G_{ij}[V_i^2 + V_j^2 - 2V_iV_j\cos(\delta_i - \delta_j)] \quad (3)$$

Above mentioned objective function is subject to following constraint [5], [9]:

$$P_{gi} = P_{di} - V_i \sum_{j\in N_i} V_j (G_{ij}\cos\delta_{ij} + B_{ij}\sin\delta_{ij}),\ i \in N_0 \quad (4)$$

$$Q_{gi} = Q_{di} - V_i \sum_{j\in N_i} V_j (G_{ij}\sin\delta_{ij} - B_{ij}\cos\delta_{ij}),\ i \in N_{PQ} \quad (5)$$

$$V_{i\,min} \le V_i \le V_{i\,max},\ i \in N_B \quad (6)$$

$$T_{i\,min} \le T_i \le T_{i\,max},\ i \in N_T \quad (7)$$

$$Q_{gi\,min} \le Q_{gi} \le Q_{gi\,max},\ i \in N_G \quad (8)$$

Where,

P_{loss} is the active power loss in the system
N_B is total number of buses
G_{ij} is the mutual conductance between buses i and j
V_i and V_j are the voltage magnitudes of buses i and j
δ_i and δ_j are the voltage phase angles of buses i and j

P_{gi} and Q_{gi} are the specified active and reactive power supply at bus i
P_{di} and Q_{di} are the specified active and reactive power demand at bus i
B_{ij} is the susceptance between buses i and j
N_0 is total number of buses except slack bus
N_{PQ} is total number of PQ buses
T_i is the tap position of transformer i
N_T is total number of transformers
N_G is total number of generator buses

Among many methods for solving load flow equations, Newton-Raphson is one of them. This paper uses this method for load flow solution. The linearized equation for this method is:

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix}\frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V}\\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial \delta}\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \Delta V\end{bmatrix} \quad (9)$$

Where, ΔP and ΔQ are the real power and reactive power mismatch vectors. ∂P/∂δ and ∂P/∂V are the partial derivative vectors of real power with respect to voltage angles and voltage magnitudes. ∂Q/∂δ and ∂Q/∂V are the partial derivative vectors of reactive power with respect to voltage angles and voltage magnitudes. Δδ and ΔV are voltage angle and voltage magnitude mismatch vectors.

C. Particle Swarm Optimization Technique (PSO)

The PSO is a stochastic, population-based problem solving algorithm based on social-psychological principle. In PSO technique, each particle can be thought of as a state of mind-as particle settings of the abstract variables that describes our beliefs and attitudes.

Equation to evaluate velocity of each particle is as follow: [6], [10]:

$$v_i = w * v_i + C_1 * \text{rand} \times (pbest_i - s_i) + C_2 * \text{rand} \times (gbest_i - s_i) \quad (10)$$

Where,

C_1 and C_2 =2 weight coefficient)
w is weight function which is given as [6],[10]:

$$w = w_{max} - \frac{w_{max} - w_{min}}{iter_{max}} * iter \quad (11)$$

And

w_{max}=Initial weight equal to 1
w_{min}=Initial weight equal to 0.3
$iter_{max}$=Maximum iteration number, and
$iter$= Current iteration number
v_i is velocity of particle i
rand is a any value between 0 and 1
$pbest_i$ and $gbest_i$ are the personal best and global best positions of particle i respectively
s_i the current position of particle i

From above equation (10), position vector is obtained by using following formula:

$$s_i = s_i + v_i$$

Computational flow of PSO algorithm used in this paper is as follows:

Step 1. (**initialization**):initializing required number of particles
Step 2. (**Time updating**):iteration counter is updated
Step 3. (**Velocity updating**): update velocity, use global best and personal (Individual) best
Step 4. (**Position updating**):Based on the updated velocities, each particle changes its position
Step 5. (**Individual best updating**):Each particles' fitness is evaluated according to its updated position
Step 6. (**Global best updating**):Search for highest fitness value among individual best
Step 7. (**Stopping criteria**): when maximum limit value for iteration counter is reached then stop else repeat from step 2 to step 6.

D. Voltage Stability Index (VSI)

Consider a system where n is the total number of buses With 1, 2… g, g number of generator buses, and g + 1. . . n, remaining buses[1],[2] and considering, I_G, I_L, and V_G, V_L complex current and voltage vectors at the generator nodes and load nodes, we can write,:

$$\begin{bmatrix} I_G \\ I_L \end{bmatrix} = \begin{bmatrix} Y_{GG} & Y_{GL} \\ Y_{LG} & Y_{LL} \end{bmatrix} \begin{bmatrix} V_G \\ V_L \end{bmatrix} \quad (12)$$

$[Y_{GG}]$, $[Y_{GL}]$, $[Y_{LG}]$ and $[Y_{LL}]$ are corresponding partitioned portions of network *Y-bus* matrix [1], [2].

Rearranging above equation, we get:

$$\begin{bmatrix} V_L \\ I_G \end{bmatrix} = \begin{bmatrix} Z_{LL} & F_{LG} \\ K_{GL} & Y_{GG} \end{bmatrix} \begin{bmatrix} I_L \\ V_G \end{bmatrix} \quad (13)$$

Where, $F_{LG} = -[Y_{LL}]^{-1}[Y_{LG}]$

We can calculate static voltage stability *L-index* as1], [2]:

$$L_j = \left| 1 - \sum_{i=1}^{g} F_{ji} \frac{V_i}{V_j} \right| \quad (14)$$

Where, j=g+1… n and F_{ji} are the complex elements of $[F_{LG}]$ matrix. The L-indices for a given load condition are computed for all load buses [1], [2].

E. Power System analysis Toolbox (PSAT)

PSAT is an open source Matlab and GNU/Octave-software package for analysis and design of small to medium size electrical power systems. Here is a PSAT plot for modified IEEE 30 bus system which clearly indicates that best location for STATCOM in normal condition is at bus 30.

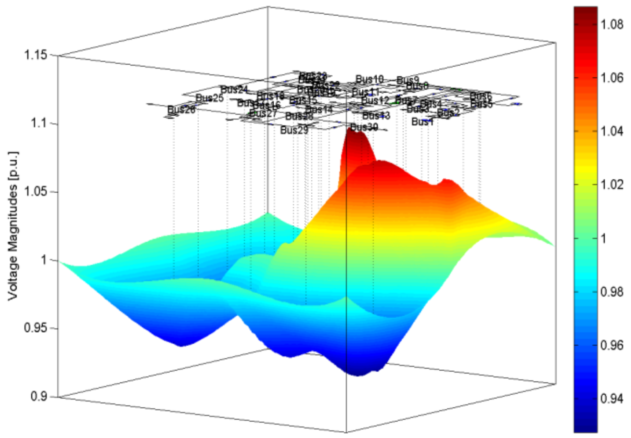

Figure 1 PSAT plot for Modified IEEE 30 bus system

III. OPTIMAL PLACEMENT OF STATCOM

A. Optimization Strategy

In this study location of STATCOM is optimized which require large number of combinational analysis. Heuristic methods solve combinational optimization problems but they have several limitation and drawbacks.

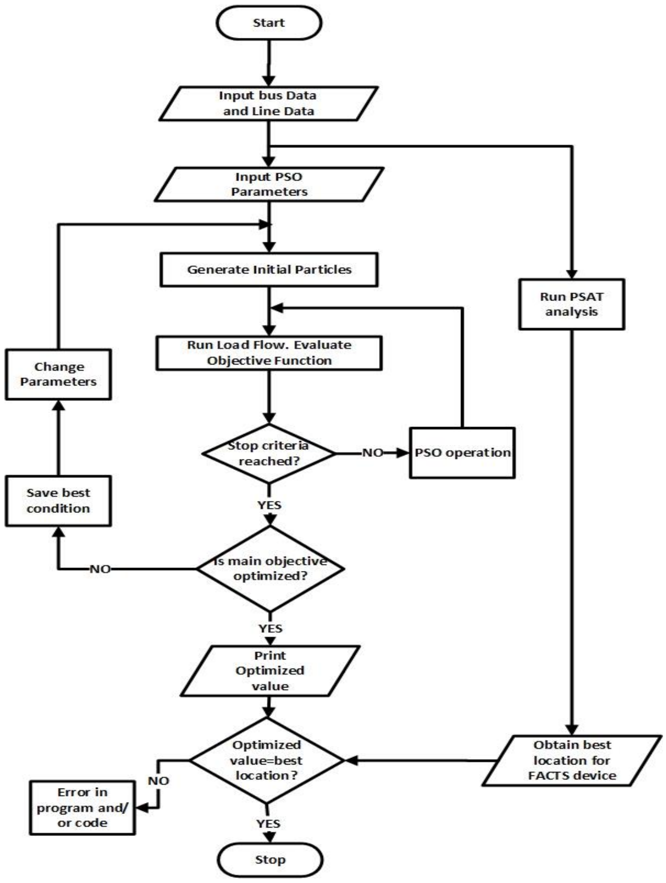

Figure 2 System Flowchart

To fulfill the above objectives, following steps can be taken:

1. Read the system parameters and configurations
2. Read the STATCOM and bus data.
3. Run PSAT analysis as well.
4. Read PSO parameters.
5. Initially set the random location of STATCOM.
6. Run the load flow which gives bus voltage of all the buses.
7. Calculate objective function.
8. Perform the PSO operation. This gives the new location of STATCOM with optimized objective function.
9. Repeat 6, 7, 8 till the criteria is met.
10. Compare algorithm result with PSAT output. If both the results are not same there is some error in the program.

B. Real power loss minimization maintaining voltage stability

The main objective of this paper is to maintain stable voltage at minimum real power loss.

$$main\ objective\ function = min(P_{loss} + L\text{-}index)$$

The new objective function will be minimization of equation (3) and (14) combined.

This objective is obtained by connecting STATCOM to the power system. Combining equation (1), (2) and (9) we get following load flow equation [7]:

$$\begin{bmatrix} \Delta P \\ \Delta Q \\ \Delta PEx \\ \Delta F \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} & \frac{\partial P}{\partial V_{st}} & \frac{\partial P}{\partial \delta_{st}} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V} & \frac{\partial Q}{\partial V_{st}} & \frac{\partial Q}{\partial \delta_{st}} \\ \frac{\partial PEx}{\partial V} & \frac{\partial PEx}{\partial V} & \frac{\partial PEx}{\partial V_{st}} & \frac{\partial PEx}{\partial \delta_{st}} \\ \frac{\partial F}{\partial V} & \frac{\partial F}{\partial V} & \frac{\partial F}{\partial V_{st}} & \frac{\partial F}{\partial \delta_{st}} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta V \\ \Delta V_{st} \\ \Delta \delta_{st} \end{bmatrix}$$

Where, ΔPE_x and ΔF are active power exchange vector and voltage magnitude mismatch vector respectively. ΔV_{st} and $\Delta \delta_{st}$ are the STATCOM voltage magnitude and angle mismatch vectors.

We will further observe the performance of system by increasing reactive load (MVAR) to different level in a specific bus and find best location of STATCOM.

C. *Criteria for optimal location*

STATCOM will be connected to every buses and value of objective function will be recorded. Minimum among these data gives best location of STATCOM.STATCOM should be placed on the bus giving the desired result.

IV. RESULTS AND DISCUSSIONS

We are using Modified IEEE 30-bus system with some Bus Data and Line data obtained from paper [12] which was tested to find the optimal location of STATCOM. The parameters for optimization technique are listed in the table below.

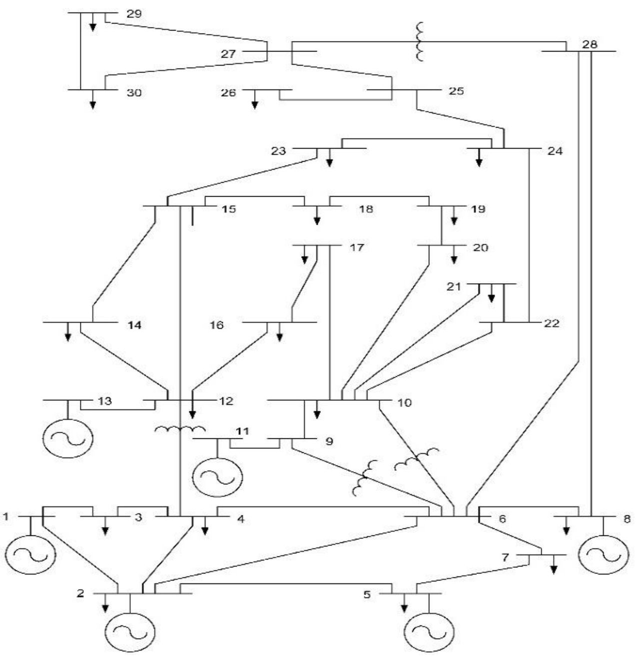

Figure 3 Modified IEEE 30 bus system

Table 1: Parameters for PSO technique

Parameters	PSO
population Size	5
Initial Weight	1-0.3
Constant,C1	2
Constant,C2	2
Number of Iteration	50
Rand1	0 to 1
rand2	0 to 1

STATCOM installation in the transmission system to reduce the transmission loss in the system and enhancement of voltage stability has been tested at several loading conditions subjected to bus 26 and 14.

A. *Transmission loss and Voltage Profile enhancement*

Result for real power loss variation at different loading Conditions at load buses 14 and 26 are shown below. In normal condition when there is no load variation at different buses, optimal location of STATCOM is at bus 30 with real power loss of 21.4563 MW.

Table 2: Real power loss and Voltage Stability Index (VSI) at different loading conditions at bus 26

S. No.	Q-demand at Bus 26[Mvar]	STATCOM connection	Real Power Loss [MW]		VSI	
			Without STATCOM	With STATCOM	Without STATCOM	With STATCOM
1	1.0	30	21.1727	19.7294	0.1380	0.0908
2	2.0	30	21.6849	19.9620	0.0675	0.0579
3	3.0	30	21.8668	19.8498	0.1870	0.1294
4	4.0	26	20.0799	18.3430	0.1248	0.0440
5	5.0	26	20.7159	18.7058	0.0973	0.0829

Reactive power demand for load bus 26 at different loading conditions (1 MVar, 2 MVar, 3 MVar, 4 MVar and 5 MVar) is recorded in table 2. Bus 26 is far from generation stations which can be seen in Modified IEEE 30-bus system alongside. Small variation in load i.e. increasing 1 MVar at a time, large variation in real power loss and voltage stability can be seen. Best location for STATCOM has change from bus 30 to bus 26 when loading condition is changed from 3 MVar to 4 MVar.

As generation stations are too far from load bus 26 as in figure 4 and 5 , transmission loss is greatly increased in the system just by increasing 1 MVar and thus best location for STATCOM has changed from bus 30 to bus 26 to meet our objective of making system more stable with reduction in transmission loss.

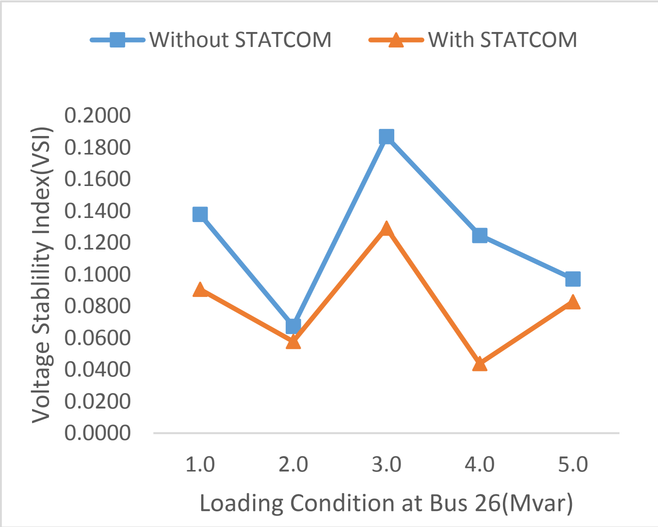

Figure 4 Power loss at different loading conditions at bus 26

We can also observe that on changing of loading condition from 3 MVar to 4 MVar, there is reduction of real power loss from 21.8668 MW to 20.0799 MW. This may be due to change in STATCOM location to the bus 26 where there is actual load demand.

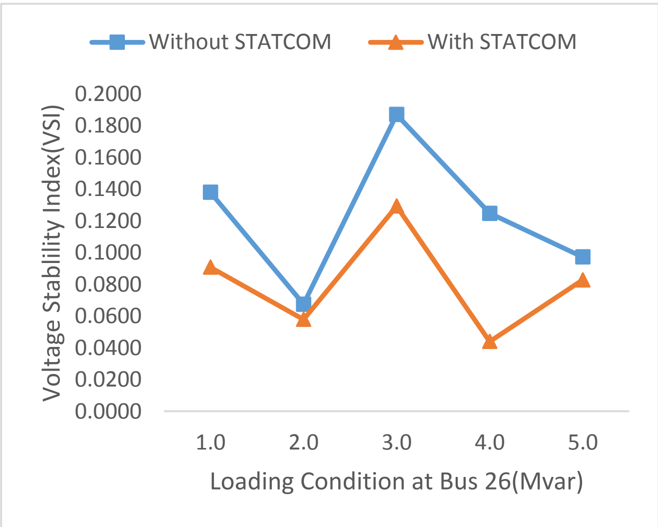

Figure 5 Plot of VSI at different loading conditions at bus 26

Reactive power demand for load bus 14 at different loading conditions (10 MVar, 20 MVar, 30 MVar, 40 MVar and 50 MVar) is recorded in table 3. Bus 14 is close to generation stations. Large variation in load is needed for significant power loss increase unlike at load bus 26 which is far from generation stations which can be seen in figure 6 and 7. When reactive power demand is increased from 30 MVar to 40 MVar, best location for STATCOM is changed from bus 30 to bus 14.

Table 3: Real power loss and Voltage Stability Index (VSI) at different loading conditions at bus 14

S.No.	Q-demand at Bus 14[MVar]	STATCOM connection	Real Power Loss [MW]		VSI	
			Without STATCOM	With STATCOM	Without STATCOM	With STATCOM
1	10.0	30	21.1531	19.7895	0.0775	0.0592
2	20.0	30	21.8298	19.9585	0.0908	0.0820
3	30.0	30	22.3558	21.0262	0.1422	0.0630
4	40.0	14	22.0439	21.1937	0.1008	0.0935
5	50.0	14	23.1428	21.9496	0.1690	0.1936

Like in the case of bus 26, we can also observe that on changing of loading condition form 30 MVar to 40 MVar, there is there is reduction of real power loss from 22.3558 MW to 22.0439 MW. This may be due to change in STATCOM location to the bus 14 where there is actual load demand.

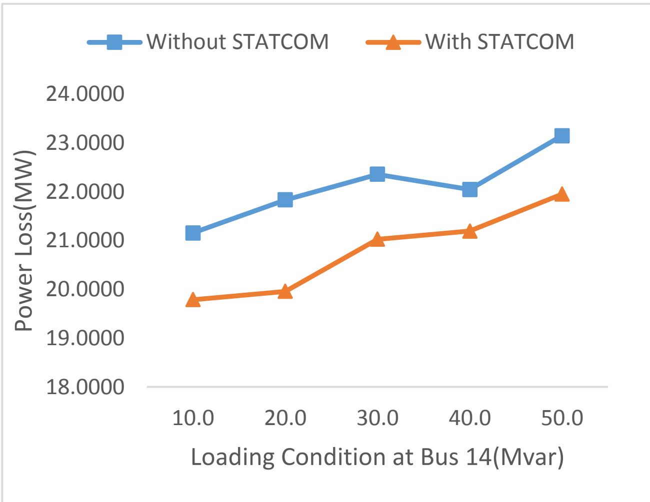

Figure 6 Power loss at different loading conditions at bus 14

With an aim to test proposed methodology in Modified IEEE 30 bus system and validate optimization technique external education/research aimed software Power System Analysis Toolbox (PSAT) is used. Voltage magnitude for different loading conditions for buses 14 and 26 are observed

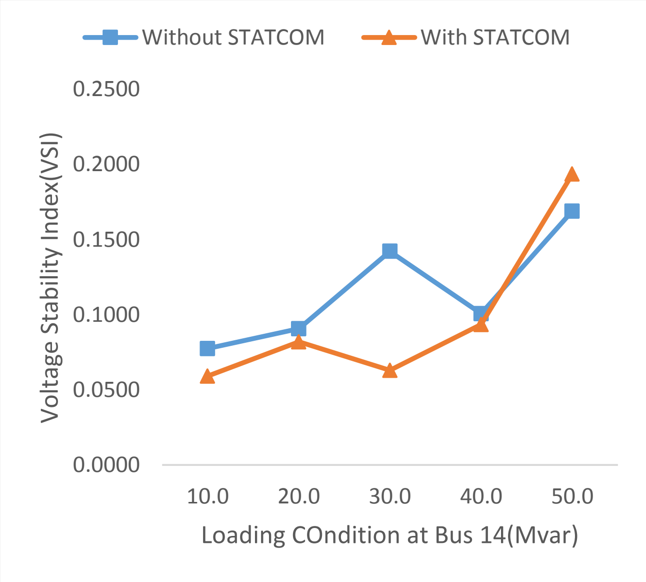

Figure 7 Plot of VSI at different loading conditions at bus 14

Voltage magnitude is lowest at bus 30 for loading condition (1 MVar, 2 MVar and 3 MVar) and for loading conditions (4 MVar and 5 MVar) voltage magnitude is lowest at bus 26 when reactive power demand for load bus 26 at different loading condition is observed.

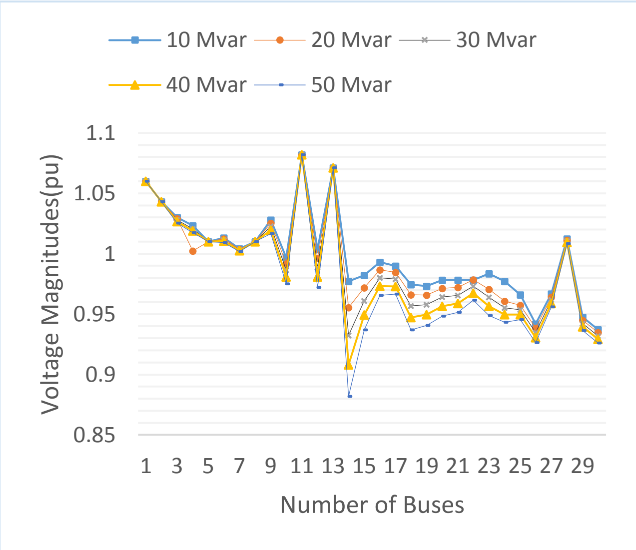

Figure 8 PSAT voltage magnitude plot for varying load at bus 26

Likewise, voltage magnitude is lowest at bus 30 for loading conditions (10 MVar, 20 MVar and 30 MVar) and for loading conditions (40 MVar and 50 MVar) voltage magnitude is lowest at bus 14 when reactive power demand for load bus 14 at different loading condition is observed.

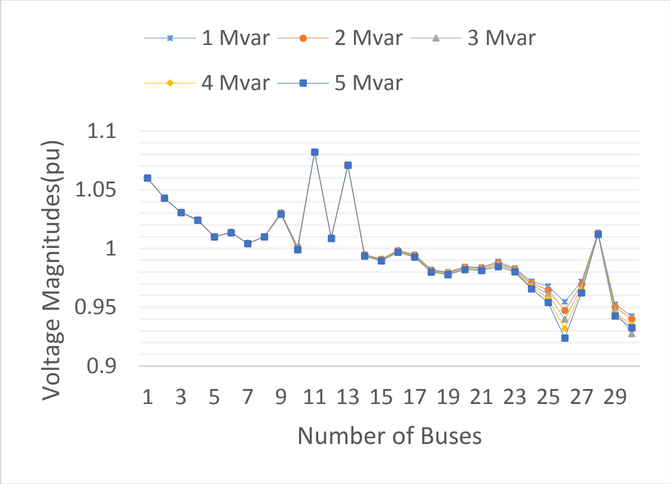

Figure 9 PSAT voltage magnitude plot for varying load at bus 14

V. CONCLUSION AND FUTURE WORKS

This paper presents a technique based on Particle Swarm Optimizations (PSO) for optimal placement of STATCOM that has been employed as power flow controller along the buses with a purpose to enhance voltage stability with congestion management achieved by real power loss minimization.

This paper uses Modified IEEE 30-bus test to evaluate the performance of the proposed approach which is verified by using external education/research aimed software Power System Analysis Toolbox (PSAT).

Further enhancement can be done to this project. We can test this approach in bigger system like IEEE 57 or IEEE 105 bus system and also real case scenario. We can also use other FACTS devices like SVC, TCSC and so on or their combination to optimize objective function. And finally, we can use different optimization technique like hybrid PSO or genetic Algorithm and different optimization criteria such as cost minimization and sizing of STATCOM.

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