Application of FACTS devices for congestion mitigation in Power System

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Abstract: *The Flexible AC Transmission System (FACTS) Devices which are used for increasing the transmission line loadability without changing its line parameters. The use of multiple combinations of FACTS devices on line may help in reducing heavy load congestion on power system lines. This may be helpful in reduction of system losses, improve system stability in terms of a small signal as well as large signal analysis with the enhancement of power quality of the existing systems. This paper scrutinizes the effect of multiple combinations of FACTS devices on load congestions mitigations with the application of WLS Technique. The system under consideration has been tested on two types of FACTS devices i.e. SVC and STATCOM. The optimal size and allocation of individual and combination of FACTS devices will lead to minimise system congestion. Such type of arrangement of FACTS device will also lead to optimize the cost of entire power system with appropriate voltage profile and Reactive power compensation. The proposed model is demonstrated on modified IEEE 14 Bus System. The IEEE 14 Bus System designed and tested on Simulation of MATLAB software.*

Keywords*: FACTS Devices, Congestion, STATCOM, SVC, WLS State Estimation technique.*

1. Introduction

The power system is a complex system where various parameters and components are associated in it. The complex network of power system in recent trend is regulated by using Decentralisation of Electricity Generation and Deregulated Power Supply. The Decentralisation in electricity generation will improve electricity generation efficiency and efficient use of their power generation sources. The Deregulation of Power Supply will help in optimisation of flow of power from generation end to consumer end in an effective way. The combination of these two things will again lead to a complex network operation where it again required an optimum utilisation of existing usage of transmission infrastructure. The presence of various sources of power generation will lead to contractual obligations amongst the power producers for effective use of their resources in fulfilling the market requirement. The optimum utilisation of transmission infrastructure incorporation of power generation is also a difficult task for power optimisation.

The location and sizing of FACTS device as per [1] for reactive power compensation in electric networks is opted by using Evolutionary Approach incorporation Genetic Algorithms. The test model tested on radial distribution network of IEEE bus system. The [2] focussed on GSA based optimisation technique in association among Genetic Algorithm, Particle Swarm Optimisation and Differential Evolution Technique for optimal placement of FACTS devices for congestion mitigation of IEEE 30 and 57 bus systems.

The [3] proposed Newton Raphson and modified simulated Annealing Technique for identification of right choice of FACTS devices combination out of TCSC, TCPST and

UPFC. The system is work on the active power flow without violation of system constraints on modified IEEE 14 bus system. The [4] suggested for improvement of total power transfer capability, decrease line congestion and power loss by use of Harmony Search Algorithm (HSA) as compared with Particle Swarm Optimisation (PSO) and Genetic Algorithm (GA) Technique. They suggested how to identify size and allocation of FACTS devices in modified IEEE 30 bus system.

The [5] demonstrate the designing of supplementary controller of STATCOM for oscillation mitigation in power systems on single machine system. The Statcom modelling with IEEE benchmark model is used. They suggested that there are four critical values of series compensation against rotor oscillations. The eigen values used for series compensation of critical values of power system. The [6] discussed various types of FACTS devices for voltage stability of power system. The continuous modes of power system are evaluated on loading condition. The modified IEEE 14 bus system tested on PSAT tool of MATLAB.

The [7] [8] suggested the Weighted Least Square (WLS) technique for finding the appropriate localization of auxiliary devices for power system compensation. The WLS and phasor measurement unit (pmu) combination are demonstrated on IEEE bus system.

The [9] deals with the Maximum loadability condition for single contingency. The placement of FACTS devices based on Contingency Severity Index (CSI) and Fast voltage stability index (FVSI) to facilitate socioeconomic benefits by minimizing installation cost of FACTS devices. The test bed is to be designed on IEEE 30 bus system by using differential evolution algorithm. The [10] suggested the use of STATCOM controller for the frequently variable load with respect to time i.e. arc furnace load. The STATCOM controller of 12 pulses and 24 pulses are discussed on PSCAD model programme.

In [11] suggested Fuzzy self tuning proportional integral (PI) control for expert decision, expert decision subsystem and differential slope voltage regulation for identification of suitability between SVC and SSSC. The system tested on dynamic loading conditions in compensation of reactive power. The [12] proposed heuristic search manner and desirability criterion to evaluate the location for FACTS devices like SSSC and STATCOM in medium and large power system. The PQ phasor are used to evaluate FACTS devices in steady state conditions. The average neural lossy model propose for minimise converter power losses.

The [13] concerted on technique based on particle swarm optimisation (PSO) for finest allocation of FACTS devices at nominal installation cost and enhance system loadability. The Thermal limit of transmission lines and Voltage limit of buses are considered as a constraint before deciding size and allocation of FACTS devices i.e. TCSC, SVC and UPFC. The device are placed single type devices and multi-type devices are allocated in system. The simulation model used are IEEE 6, 30 and 118 bus systems with Tamil Nadu Electricity Board (TNEB) 69 bus system. In the [14], discussing parameters are controlling of transmission voltage, power flow, damping of power system oscillation and reactive power losses by use of Shunt FACTS devices. They suggested that the requirement of shunt devices depend upon series compensation of existing system.

The [15] proposed the system with improved voltage stability margin by control on reactive power limit of power system. The system tested on IEEE 14 bus system with STATCOM by modelling & simulation on MATLAB sim power system tool box. The [16] recommended that multiple FACTS devices which may diminish congestion in heavy loaded lines condense on system losses, improvement in system stability and energy cost reduce on power system. The FACTS devices i.e. TCSC, STATCOM and UPFC recommended in multiple combination for congestion mitigation of power system.

The [17] suggested that reliability, stability and security are prime parameters of power system. All these parameters are important for system voltage stability. The STATCOM used on IEEE 14 Bus system by using of Fast Voltage Stability Index (FVSI), Line Stability Index (Lmn) and Line Stability Factor (LQP) for identification of weak buses of system. The Continuation Power Flow (CPF) of MATLAB used for placement of STATCOM. The [18] demonstrated humeral immune voltage control with self and non self antigen intrusion on 10 machine 39 node power system. The STATCOM with humeral technique for control of voltage variations and power system limit violation are discussed.

The allocation of sections in this paper is aligned as: Section 2: provide information related to steady state modelling of FACTS Devices; Section 3: provide WLS State Estimation technique process; Section 4: gives proposed Simulation model and their finding tested on IEEE 14 Bus system with SVC and STATCOM; Section 5: concentrate on finding and their comparison on the basis of the result achieved on Test model followed by conclusion.

2. Modelling of facts devices:

2.1 Modelling of SVC

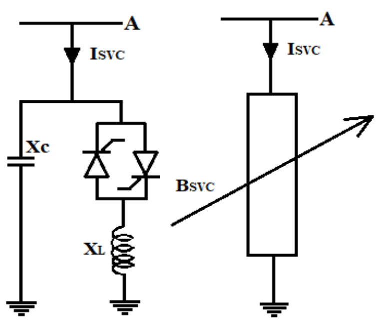

Fig.1 SVC

SVC is a Static VAR compensator of FACTS Devices is connected in Shunt and main functionality is to regulate voltage at a given Bus by controlling its equivalent reactance [12]. It consists of fixed capacitor (FC) and Thyristor controlled Reactor (TCR). Generally there are two configuration of the SVC [9] [13]

A. SVC Total susceptance model.

B. SVC firing angle model.

$$I_{SVC} = -j\, B_{SVC}\, V_a \tag{1}$$

Where $B_{SVC} = -{}^{1}/_{X_{SVC}}$

On Fundamental frequency TCR equivalent reactance X_{TCR} is

$$X_{TCR} = \frac{\pi X_L}{\sigma - \mathrm{Sin}\,\sigma} \tag{2}$$

Where $\sigma = 2(\pi - \alpha)$, $X_L = \omega L$ and TCR in terms of firing angle is as

$$X_{TCR} = \frac{\pi X_L}{2(\pi - \alpha) + \mathrm{Sin}\,(2\alpha)} \tag{3}$$

Where α and σ are firing and conduction angles of TCR respectively. The firing angle of TCR is varied from 0^o to 180^o.

The parallel combination of X_C and X_{TCR} are determine value of effective reactance of SVC [16] [19] as X_{SVC}

$$X_{SVC} = \frac{\pi X_L X_C}{X_C\,[\,2(\pi - \alpha) + \mathrm{Sin}\,(2\alpha)] + \pi X_L} \tag{4}$$

Where $X_C = {}^{1}/_{\omega C}$ and

$$Q_a = -V_a^2 \frac{X_C\,[\,2(\pi-\alpha)+\mathrm{Sin}\,(\,2\alpha\,)]+\pi\,X_L}{\pi\,X_L X_C} \tag{5}$$

The proposed model of SVC is considered firing angle as the state variable in formulation of power flow analysis. So that the linearised power flow equation may be formulated as

$$\begin{bmatrix}\Delta P_a\\ \Delta Q_a\end{bmatrix}^i = \begin{bmatrix}0 & 0\\ 0 & \frac{2V_a^2}{\pi X_L}[\mathrm{Cos}(2\alpha)-1]\end{bmatrix}^i \begin{bmatrix}\Delta\theta_a\\ \Delta\alpha\end{bmatrix}^i \tag{6}$$

The process to be continued till end of the iteration i and the variable firing angle is updated accordingly

$$\alpha^i = \alpha^{i-1} + \Delta\alpha^i$$

2.2 Modelling of STATCOM

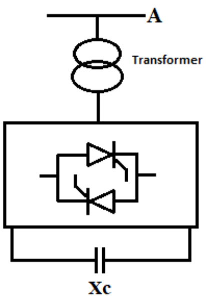

Fig.2 STATCOM

STATCOM is a Static Synchronous Compensator of FACTS Devices using to control power flow of system and improve transient stability of power system. The STATCOM may be represented as STATCOM voltage source [3] [14] $V_{SV}\angle\theta_{SV}$ with series impedance of ZSV at bus voltage of$V_a\angle\theta_a$. Assuming system is consisting of bus-bar, transformer, series impedance and a STATCOM [5] [19], are represented as:

$$E_{SV} = V_{SV}\angle\delta_{SV} = V_{SV}\,(\,\mathrm{Cos}\,\delta_{SV} + j\,\mathrm{Sin}\,\delta_{SV}\,) \tag{7}$$

$$Y_{SV} = 1/(\,Z_{SV}\angle\theta_{SV}) = G_{SV} + j\,B_{SV} \tag{8}$$

We know that

$$S_{SV} = P_{SV} + j\,Q_{SV} = I_{SV}^*\,V_{SV} = V_{SV}\,Y_{SV}^*\,(\,V_{SV}^* - V_a^*\,) \tag{9}$$

The following equations are obtained after realisation of above equation into real & imaginary parts at bus 'a' are as follows

$$P_{SV} = V_{SV}^2\,G_{SV} + V_{SV}\,V_a[\,G_{SV}\,\mathrm{Cos}\,(\delta_{SV}-\theta_a) + B_{SV}\,\mathrm{Sin}\,(\delta_{SV}-\theta_a)] \tag{10}$$

$$Q_{SV} = -V_{SV}^2\,G_{SV} + V_{SV}\,V_a[\,G_{SV}\,\mathrm{Cos}\,(\,\theta_a - \delta_{SV}) + B_{SV}\,\mathrm{Sin}\,(\theta_a - \delta_{SV})] \tag{11}$$

$$P_a = V_a^2\,G_{SV} + V_{SV}\,V_a[\,G_{SV}\,\mathrm{Cos}\,(\delta_{SV}-\theta_a) + B_{SV}\,\mathrm{Sin}\,(\delta_{SV}-\theta_a)] \tag{12}$$

$$Q_a = -V_a^2\,G_{SV} + V_{SV}\,V_a[\,G_{SV}\,\mathrm{Cos}(\,\theta_a - \delta_{SV}) + B_{SV}\,\mathrm{Sin}\,(\theta_a - \delta_{SV})] \tag{13}$$

$$\begin{bmatrix} \Delta P_a \\ \Delta Q_a \\ \Delta P_{SV} \\ \Delta Q_{SV} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_a}{\partial \theta_a} & \frac{\partial P_a}{\partial V_a} V_a & \frac{\partial P_a}{\partial \delta_{SV}} & \frac{\partial P_a}{\partial V_{SV}} V_{SV} \\ \frac{\partial Q_a}{\partial \theta_a} & \frac{\partial Q_a}{\partial V_a} V_a & \frac{\partial Q_a}{\partial \delta_{SV}} & \frac{\partial Q_a}{\partial V_{SV}} V_{SV} \\ \frac{\partial P_{SV}}{\partial \theta_a} & \frac{\partial P_{SV}}{\partial V_a} V_a & \frac{\partial P_{SV}}{\partial \delta_{SV}} & \frac{\partial P_{SV}}{\partial V_{SV}} V_{SV} \\ \frac{\partial Q_{SV}}{\partial \theta_a} & \frac{\partial Q_{SV}}{\partial V_a} V_a & \frac{\partial Q_{SV}}{\partial \delta_{SV}} & \frac{\partial Q_{SV}}{\partial V_{SV}} V_{SV} \end{bmatrix} \begin{bmatrix} \Delta \theta_a \\ \frac{\Delta V_a}{V_a} \\ \Delta \delta_{SV} \\ \frac{\Delta V_{SV}}{V_{SV}} \end{bmatrix} \quad (14)$$

The general information related to IEEE 14 Bus System [7] [15] on per unit basis on normal loading conditions are mentioned in tabular form are as follows:-

Table 1 Base Case of IEEE 14 Bus Systems

Bus No.	Bus Voltage (pu)	Voltage Angle (deg.)(pu)	P WATT (pu)	Q VAR (pu)
1	1.7012	1.0394	0.0123	0.0803
2	1.4328	0.9615	-0.015	0.0153
3	1.1047	0.8351	0.0141	0.0057
4	1.0110	0.7908	-0.002	-0.005
5	0.9979	0.7843	-0.049	-0.044
6	1.3807	0.9440	0.0096	0.0734
7	1.0881	0.8275	-0.001	-0.003
8	1.6916	1.0369	-0.002	-0.032
9	0.9584	0.7642	0.0172	0.0114
10	0.9464	0.7579	0.0000	0.0000
11	0.9696	0.7700	-0.003	0.006
12	0.9696	0.7700	0.002	0.0067
13	0.9659	0.7680	0.0127	0.0165
14	0.9439	0.7565	-0.000	0.001

3. WLS State Estimation Method

Let us consider the measurement set of network system are given as vector z:-

$$z = h(x) + e \quad (15)$$

Where:

$$h^T = [h_1(x), h_2(x), h_3(x), \dots \dots . h_m(x)] \quad (16)$$

hi (x) is the non-linear function related with measurement i to the state vector x

$x^T = [x^1, x^2, x^3 \dots\dots\dots\dots x^n]$ is the state vector of network system

$e_T = [e_1\ e_2\ e_3 \dots\dots\dots e_m]$ is the error measurement in state vector.

The full weighted least square estimator [7] [8] will help in diminish the following objective function:

$$J(x) = \sum_{i=1}^{m} \frac{(z_i - h_i(x))^2}{R_{ii}} = [z - h(x)]^T R^{-1} [z - h(x)] \quad (17)$$

At bare minimum value of objective function, the first-order optimum condition to be satisfied. It can be expressed as follows:

$$g(x) = \frac{\partial J(x)}{\partial x} = -H^T(x)R^{-1}[z - h(x)] = 0 \tag{18}$$

The non-linear function g(x) of Taylor series can be expanded for the state vector x^k by neglecting the higher order terms [8] will be as

$$g(x) = g(x^k) + G(x^k)(x - x^k) + \ldots\ldots.. = 0 \tag{19}$$

The Gauss-Siedel method is used to solve the above equation:

$$x^{k+1} = x^k - [G(x^k)]^{-1} . g(x^k) \tag{20}$$

Where, k is the iteration index, x^k is the state vector at iteration k and G(x) is called the gain matrix and expressed as:

$$G(x) = \frac{\partial g(x^k)}{\partial x} = H^T(x^k)R^{-1}H(x^k) \tag{21}$$

$$g(x^k) = -H^T(x^k)R^{-1}[z - h(x^k)] \tag{22}$$

Normally, the gain matrix is sparse matrix and decomposed into triangular factors. At each iteration k, the gain matrix are solved by using forward / backward substitutions, where $\Delta x^{k+1} = x^{k+1} - x^k$ and

$$[G(x^k)]\,\Delta x^{k+1} = H^T(x^k)R^{-1}[z - h(x^k)] = H^T(x^k).R^{-1}\Delta z^k \tag{23}$$

These iterations are going on till the maximum variable difference satisfies the condition, ' Max $|\Delta x^k| < \varepsilon'$.

The percentage variation in parameter to be calculated by using following relations:

$$\%age\ Variation = \frac{Values\ after\ FACTS - Values\ before\ FACTS}{Values\ after\ FACTS}\ x\ 100\% \tag{24}$$

During measurement of relevant parameters of IEEE Bus are performed with the WLS Technique. This technique is more precise and accurate during measurement of multiple parameters of buses.

3.1 WLS Technique along with facts devices are as:

1. Study input data of the power system;
2. When FACTS device implement to node k then analyse Modified admittance matrix (Y bus)
3. Merge both power equations and network equation,
4. The inclusion of facts devices with traditional jacobian matrix then these parameters increases their jacobian matrix dimensions.
5. Then WLS state estimation technique pursue from equation 15 to 24.

4. Simulation result and discussion

4.1 Implementation of multiple SVC

The Table 2 shows the working performance of single, double and triples SVC implementation in IEEE 14 Bus System. The performance of SVC implementation on power system [1] [4] will practically shows their impact on the voltage profile and reactive power compensation. The objective of the paper is to locate SVC at that location [2] [13] where voltage magnitude of the bus falls below a specific level on full load conditions and how we can bring it back to 1.0 p.u.

The Single SVC implementation [16] is connected to Bus 12, 13 and 14 individually during an independent operation of the system. The reactive power required to achieve 1.0 pu on respective bus voltage is as -0.0123, -0.0176 and -0.0049 pu respectively. The effect of Double SVC executed among IEEE bus 12 - 13, 13 - 14 and 12 - 14 respectively will lead to supply Reactive power to system are as -0.0007 & -0.0154, -0.0155 & -0.0159 and -0.0006 & -0.0149 pu respectively. The effect of Triple SVC executed on IEEE Bus 12 - 13 - 14, which will lead to supply Reactive power to the system are as -0.0007, -0.01807 and -0.0173 pu respectively.

Table 2 Effect of multiple SVC implementations

No. of SVC	SVC Parameter (pu)					
	Bus Voltage without SVC			Bus Voltage with SVC		
	V12	V13	V14	V12	V13	V14
Single	0.970	0.966	0.944	1.138	0.997	1.199
Double	0.970	0.966	----	1.310	1.187	----
	----	0.966	0.944	----	1.194	1.587
	0.970	----	0.944	1.275	----	1.537
Triple	0.970	0.966	0.944	1.356	1.288	1.654
No. of SVC	Reactive Power without SVC			Reactive Power with SVC		
	Q12	Q13	Q14	Q12	Q13	Q14
Single	0.007	0.017	0.0004	-0.012	-0.018	-0.005
Double	0.007	0.017	----	-0.001	-0.015	----
	----	0.017	0.0004	----	-0.016	-0.016
	0.007	----	0.0004	-0.001	----	-0.015
Triple	0.007	0.017	0.0004	-0.001	-0.018	-0.017

On comparison of above all cases, the objective of IEEE 14 Bus System [7] [8] is to achieve a specified level of bus voltage of 1.0 pu or above on highly loaded condition of buses of the system. The position of SVC and effect of implementing Single, Double and Triple SVC on IEEE 14 Bus System are shown in Figures 3 - 9.

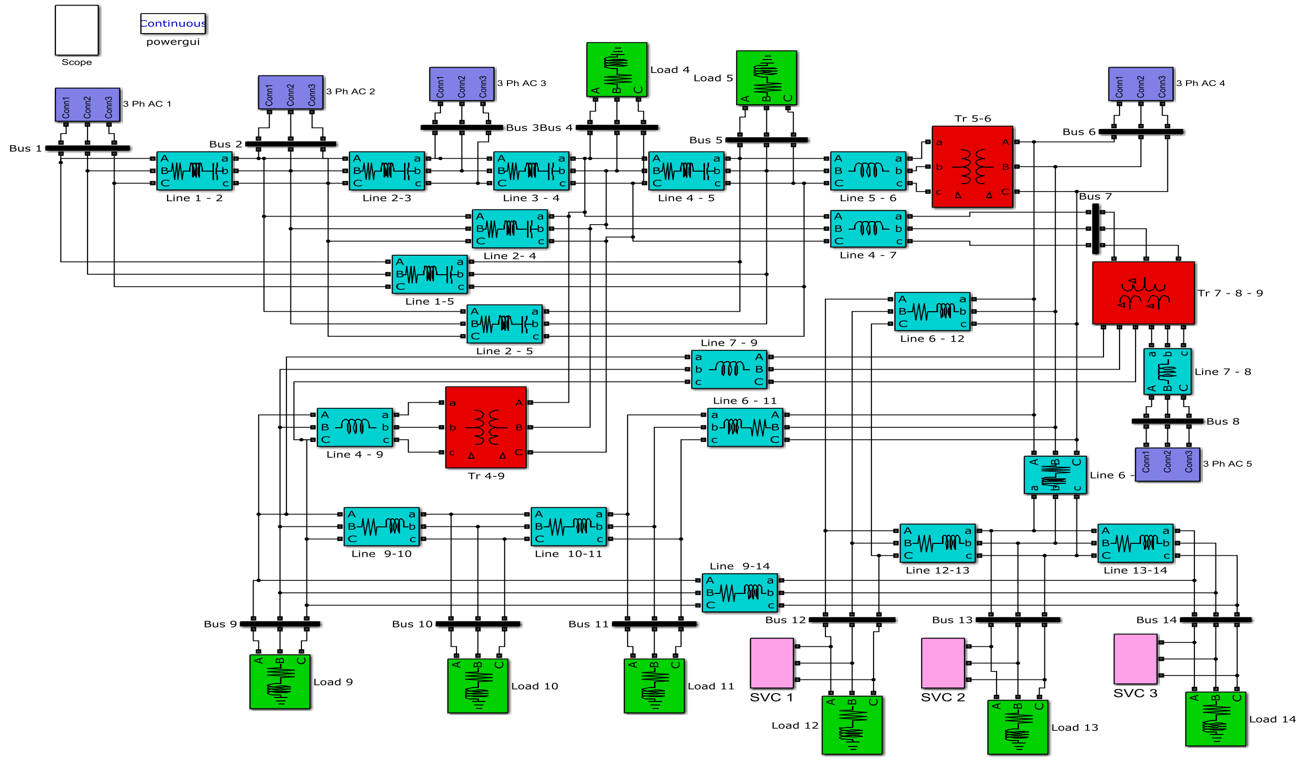

Fig.3. IEEE 14 Bus System with SVC

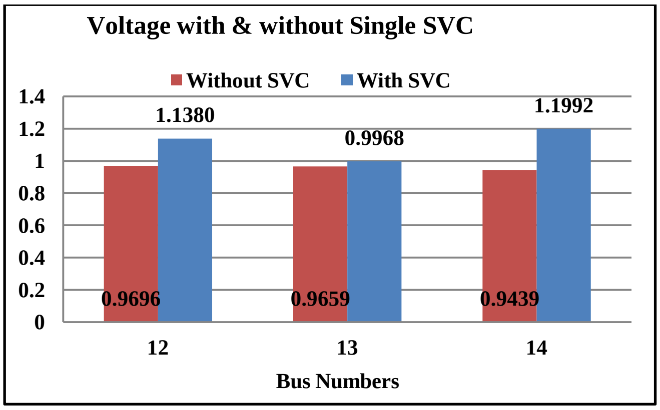

Fig.4. Performance of Voltage with Single SVC

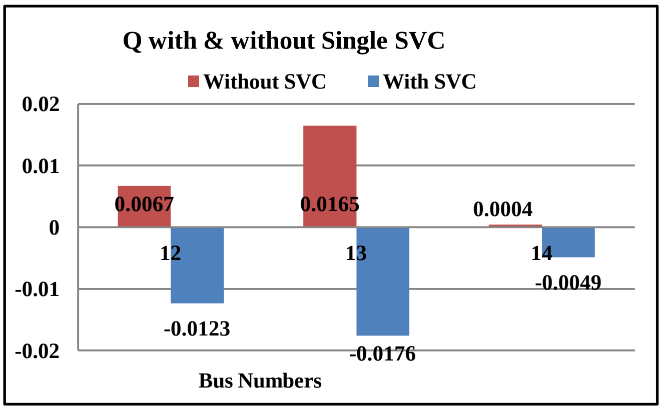

Fig.5. Performance of Reactive Power with Single SVC

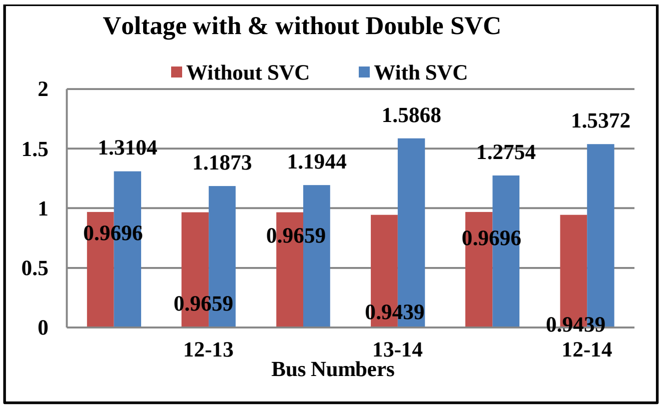

Fig.6. Performance of Voltage with Double SVC

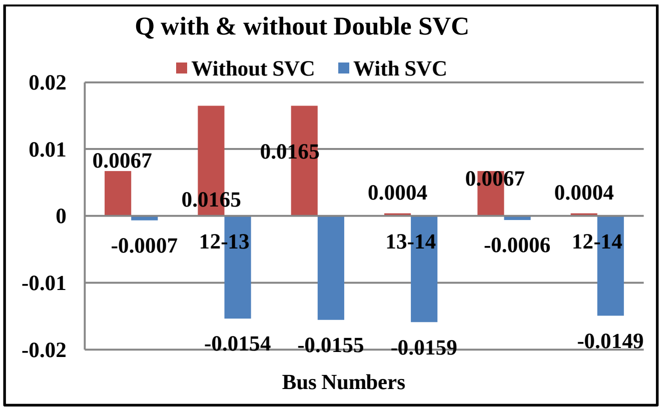

Fig.7. Performance of Reactive Power with Double SVC

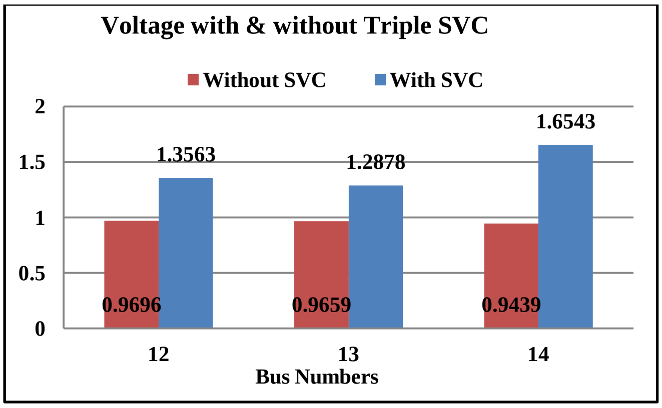

Fig.8. Performance of Voltage with Triple SVC

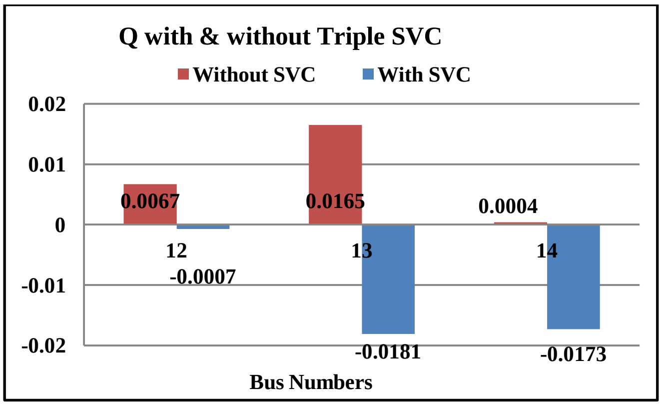

Fig.9. Performance of Reactive Power with Triple SVC

4.2 Implementation of multiple STATCOM

Table 3 shows the working performance of single, double and triple STATCOM implementation in IEEE 14 Bus System [5] [6]. The objective of the research paper is to locate STATCOM [18] at that location where bus voltage of the system is fall below a specific level at full load conditions. And also decide the size of STATCOM [10] [11] to bring back bus voltage to 1.0 p.u.

The Single STATCOM implementation is connected on Bus 12, 13 and 14 individually during an independent operation of the system. The reactive power required to achieve 1.0 pu on respective bus voltage is as -0.012, -0.018 and -0.005 pu respectively. The effect of Double STATCOM executed among IEEE bus 12 - 13, 13 - 14 and 12 - 14 respectively will lead to supply Reactive power to system are as -0.012 & -0.024, -0.024 & -0.005 and -0.012 & -0.005 pu respectively. The effect of Triple STATCOM executed on IEEE Bus 12 - 13 - 14, which will lead to supply Reactive power to system are as -0.0120, -0.0222 and -0.0049 pu respectively.

Table 3 Effect of multiple STATCOM implementations

No. of FACTS	STATCOM Parameter (pu)					
	Bus Voltage without STATCOM			Bus Voltage with STATCOM		
	V12	V13	V14	V12	V13	V14
Single	0.970	0.966	0.944	1.138	0.997	1.199
Double	0.970	0.966	----	1.151	1.049	----
	----	0.966	0.944	----	1.066	1.237
	0.970	----	0.944	1.149	----	1.227
Triple	0.970	0.966	0.944	1.166	1.083	1.272
No. of FACTS	Reactive Power without STATCOM			Reactive Power with STATCOM		
	Q12	Q13	Q14	Q12	Q13	Q14
Single	0.007	0.017	0.0004	-0.012	-0.018	-0.005
Double	0.007	0.017	----	-0.012	-0.024	----
	----	0.017	0.0004	----	-0.024	-0.005
	0.007	----	0.0004	-0.012	----	-0.005
Triple	0.007	0.017	0.0004	-0.012	-0.022	-0.005

On comparison of above all cases, the objective of IEEE 14 Bus System [15] [17] to achieve a specified level of bus voltage of 1.0 pu or above on highly loaded condition of buses of the system. The position of STATCOM and effect of implementing Single, Double and Triple STATCOM on IEEE 14 Bus System are shown in Figures 10 - 16.

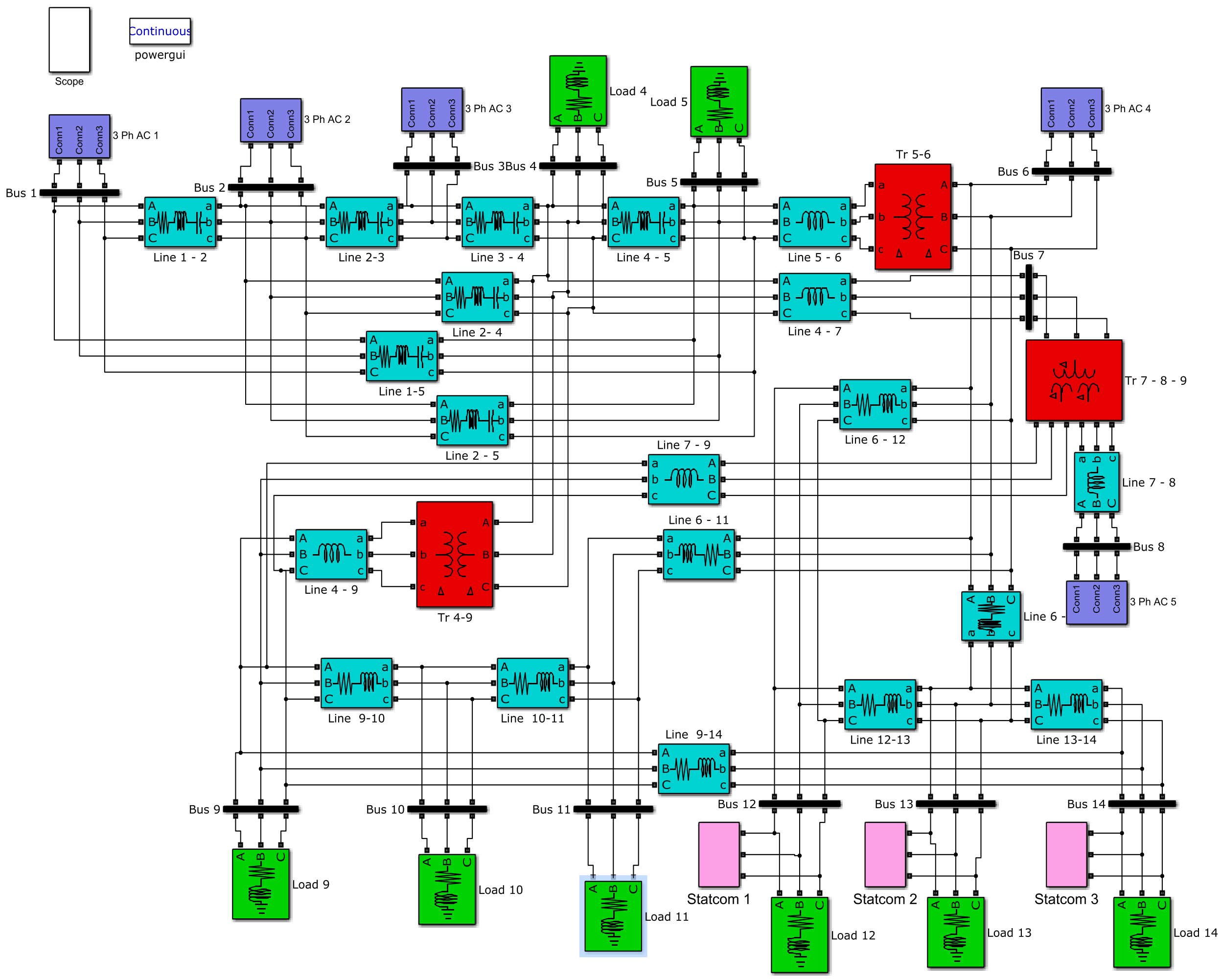

Fig.10. IEEE 14 Bus System with STATCOM

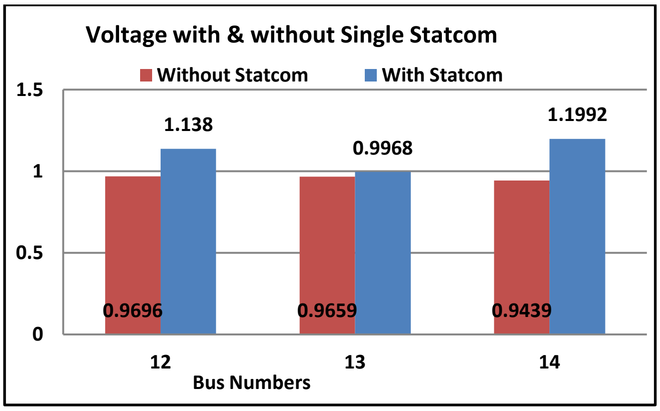

Fig.11. Performance of Voltage with Single STATCOM

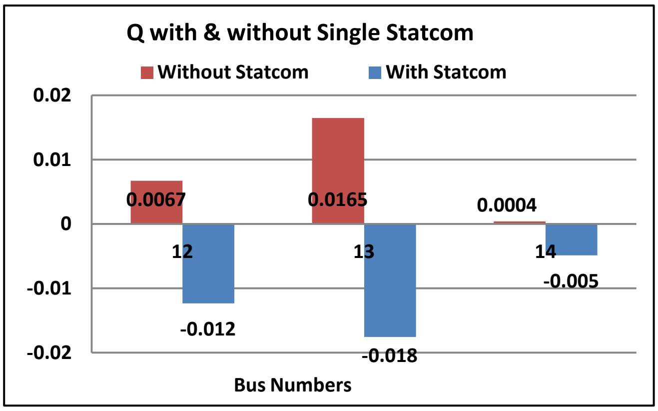

Fig.12. Performance of Reactive Power with Single STATCOM

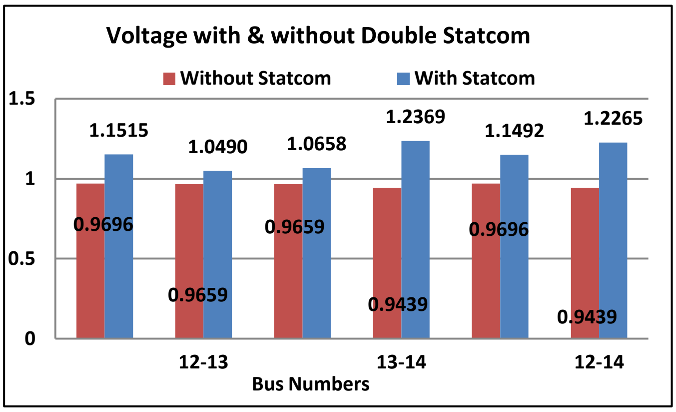

Fig.13. Performance of Voltage with Double STATCOM

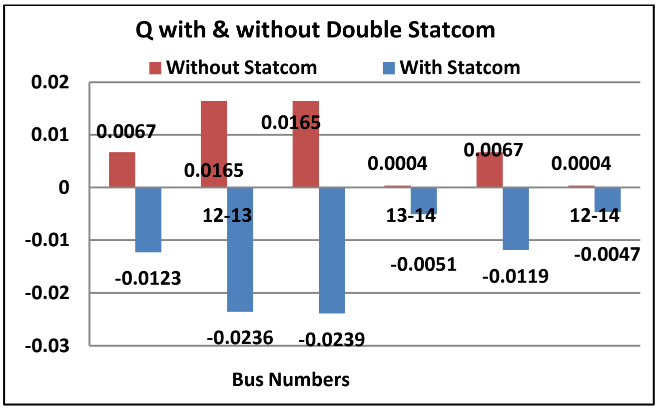

Fig.14. Performance of Reactive Power with Double STATCOM

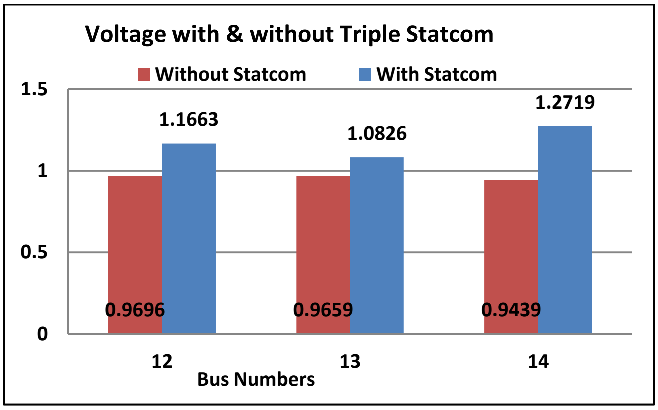

Fig.15. Performance of Voltage with Triple STATCOM

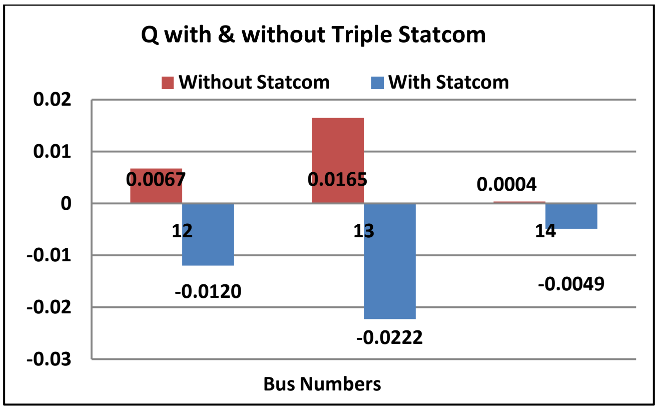

Fig.16. Performance of Reactive Power with Triple STATCOM

5. Conclusion

The multiple combinations of SVC and STATCOM were realized on an IEEE 14 Bus System. The FACTS devices implemented individually in IEEE system in the form of Single, Double and Triple device arrangement. The implementation of multiple devices will lead to reducing load congestion of the power system. The cost of the entire system will increase as multiple FACTS devices implemented in power system.

It is observed from results that while implementation of a single unit of large rating FACT device in IEEE System will not lead as much compensation as by using multiple small rating FACT devices at a different location in the system. This may lead to much more congestion relief of power system during its loading conditions. The use of Single SVC will lead to improvement in terms of standard deviation in voltage profile from 1.39% to 10.38%. While Double SVC is help improve voltage profile from 2.6% to 27.75%. And with triple SVC system will improve voltage profile from 1.39% to 19.48%. With SVC, the Reactive Power of entire system improved in terms of standard deviation from 0.64% to 1.04%.

Similarly, Single STATCOM implementation in power system during loading condition will lead to improving voltage profile in terms of standard deviation from 1.39% to 10.38%. While double STATCOM is improving voltage profile from 0.26% to 12.10% and triple STATCOM will lead to improving from 1.39% to 9.49%. The overall Reactive Power of IEEE System in cooperation with STATCOM will lead to improving in terms of standard deviation from 0.64% to 0.87%.

Finally, we find that the SVC will offer a much better load congestion relief as compared to STATCOM device due to simultaneous control over each - and - every phase of the power supply. The SVC also offers an improvement in voltage profile and more reactive power compensation as compared to STATCOM. The FACTS devices will offer a better load congestion relief to power system independently without suspicions of market forces and type of market model to have opted.

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