SENSITIVITY APPROACH TO IMPROVE TRANSFER CAPABILITY THROUGH OPTIMAL PLACEMENT OF TCSC AND SVC

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ABSTRACT

Total Transfer Capability (TTC) forms the basis for Available Transfer Capability (ATC). ATC of a transmission system is a measure of unutilized capability of a system at a given time. The computation of ATC is very important to transmission system security and market forecasting This paper focuses on the evaluation of impact of Thyristor Controlled Series Capacitor (TCSC) and Static VAR Compensator (SVC) as FACTS devices on ATC and its enhancement .The optimal location of FACTS devices were determined based on Sensitivity methods. The Reduction of Total System Reactive Power Losses Method was used to determine the suitable location of TCSC and SVC for ATC enhancement. The effectiveness of proposed method is demonstrated on modified IEEE-14 bus system.

KEYWORDS: *Deregulated power system, ATC, TTC, TCSC, SVC, Reduction of Total System Reactive Power Losses Method.*

I. INTRODUCTION

Electric utilities around the world are confronted with restructuring, deregulation and privatization. The concept of competitive industries rather than regulated ones has become prominent in the past few years [5]. Power system transfer capability indicates how much inter area power transfers can be increased without compromising system security. The Deregulated power system have to deal with problem raised by the difficulties in building new transmission lines and the significant increase in power transactions associated to competitive electricity markets[9]. It can led to a much more intensive shared use of existing transmission facilities [1].

In this situation one of the possible solutions to improve system operation is the use of Flexible AC Transmission Technologies. In recent years, the impacts of FACTS devices on power transfer capability enhancement and system loss minimization have been a major concern in the competitive electric power systems. FACTS devices makes it possible to use circuit reactance, voltage magnitude, and phase angle as controls to redistribute line flow and regulate voltage profile. Theoretically FACTS devices can offer an effective and promising alternative to conventional methods of ATC enhancement [20].

Total Transfer Capability (TTC) is the largest value of electric power that can be transferred over the interconnected transmission network in a reliable manner without violation of specified constraints. TTC is the key component for computing Available Transfer Capability (ATC).The relationship of TTC and ATC is described in NERC report: ATC equals TTC less the sum of the Transmission Reliability Margin (TRM), Existing Transmission Commitments (ETS) and Capacity Benefit Margin (CBM) [2].

Although many methods and techniques have been developed, very few methods are practical for large realistic applications for computing TTC [2]. They are

1) Continuation Power Flow (CPF) method.
2) Optimal Power Flow (OPF) method.
3) Repeated Power Flow (RPF) method.

In principle, CPF increases the loading factor in discrete steps and solves the resulting power flow problem at each step. CPF yields solutions at voltage collapse points. However, since CPF ignores the optimal distribution of the generation and the loading together with the system reactive power, it can give conservative transfer capability results. The implementation of CPF method is however complicated mathematically [5]. The optimal power flow (OPF) is a modification of CPF approach. This method is based on full AC power flow solutions which accurately determines the reactive power flow, and voltage limits as well as the line flow effect. The objective function is to maximize total generation supplied and load demand at specific buses [5].The optimal power flow based ATC calculation enables transfers by increasing the load, with uniform power factor, at a specific load bus or every load bus in the every sink area, and increasing the real power injected at a specific generator bus or several generators in the source control area until limits are incurred.

The RPF method, which repeatedly solves power flow equations at a succession of points along the specified load /generation increment, is used in this work for TTC calculation. Compared with SCOPF and CPF, the implementation of RPF is much easier and it also provides part of V-P, V-Q curve, which facilitates the potential analysis of voltage stability [2]. Repeated power flow starts from base case and repeatedly solves the power flow equations each time increasing the power transfer by a small increment until an operation limit is reached. In this dissertation, this method is usually adopted to solve ATC [1].

Various Sensitivity methods are used to determine the optimal location of FACTS to achieve different objectives. In this paper, a methodology to perform the load flow analysis have been discussed in the sections 2&3.The static modeling of FACTS devices have been proposed in the section 4 for TCSC and SVC. The Reduction of Total System Reactive Power Losses Method was used to determine the suitable location of TCSC and SVC for ATC enhancement [17]. The Simulation results have been explained in the section 6.

II. PROBLEM FORMULATION

A simple interconnected power system can be divided in to three kinds of areas: receiving area, sending area, and external areas. The Newton-Raphson equations are cast in natural power system form solving for voltage magnitude and angle, given real and reactive power injections and it is used in the calculation of transfer capability. The mathematical formulation can be expressed as follows:

Subject to power flow equations:

$$P_i = \sum_{j=1}^{n} |V_i|\,|V_j|\,|Y_{ij}|\cos(\theta_{ij} - \delta_i + \delta_j) \quad (2.1)$$

$$Q_i = -\sum_{i=1}^{n} |V_i|\,|V_j|\,|Y_{ij}|\sin(\theta_{ij} - \delta_i + \delta_j) \quad (2.2)$$

And Operational constraints are:

$$P_{g\,\min} \leq P_g \leq P_{g\,\max} \quad (2.3)$$

$$Q_{g\,\min} \leq Q_g \leq Q_{g\,\max} \quad (2.4)$$

$$S_{ij} \leq S_{ij\,\max} \quad (2.5)$$

$$V_{i\,\min} \leq V_i \leq V_{i\,\max} \quad (2.6)$$

The objective function to be optimized is:

$$P_r = \sum_{m \in R, k \notin R} P_{km} \quad (2.7)$$

Where,
P_i, Q_i = Net real and reactive power at bus i
n = set of all buses
R = set of buses in receiving area
m = bus in receiving area
k = bus not in receiving area
P_r = real power interchange between areas
P_{km}=tie line real power flow (from bus-k in sending area to bus m in receiving area)
Y_{ij},θ_{ij}=magnitude and angle of ij^{th} element of admittance of matrix
V_i, δ_i = magnitude and angle of voltage at i^{th} bus
P_g, Q_g = real and reactive power output of generator.
δ_{ij} = apparent power flow through transmission line between bus i and j.

III. METHODOLOGY

In this work, it is proposed to utilize the repeated power flow (RPF) method for the calculation of transfer capabilities due to the easy of implementation. This method involves the solution of a base case, which is the initial system conditions, and then increasing the transfer. After each increase, another load flow is solved and the security constraints tested. This method is relatively straight forward and can take into account many factors, depending on the load flow used. This method is implemented using the following computational procedure [1].
1) Establish and solve for a base case
2) Select at transfer case
3) Solve for the transfer case
4) Increase step size if transfer is successful
5) Decrease step size if transfer is unsuccessful
6) Repeat the procedure until minimum step size reached

The flow chart of the proposed method for the calculation of transfer capability is given in figure 3.1

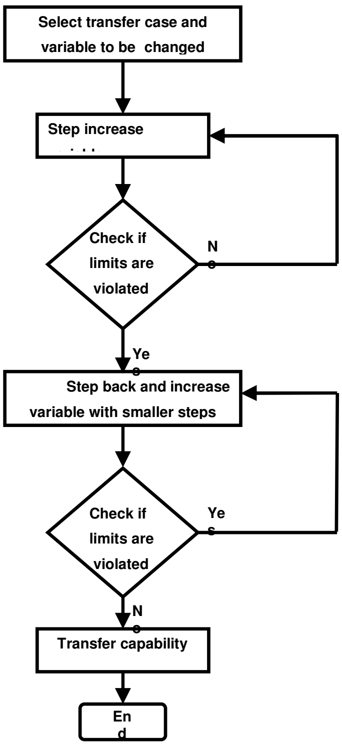

Figure 3.1:flow chart for power transfer capability.

IV. STATIC MODELING OF FACTS

In this section we look at treating enhancing the available transfer capability with the help of FACTS devices. Two main types of FACTS devices considered here are TCSC and SVC.

4.1. Static modeling of TCSC: [9]

Thyristor-controlled series capacitors (TCSC) are connected in series with the lines. The effect of a TCSC on the network can be seen as a controllable reactance inserted in the related transmission line that compensates for the capacitive reactance of the line. Figure 4.1 shows a model of a transmission line with a TCSC connected between buses *i* and *j*. The transmission line is represented by its lumped ∏-equivalent parameters connected between the two buses. During the steady state, the TCSC can be considered as a static reactance *-jxc*. This controllable reactance, *xc*, is directly used as the control variable to be implemented in the power flow equation.

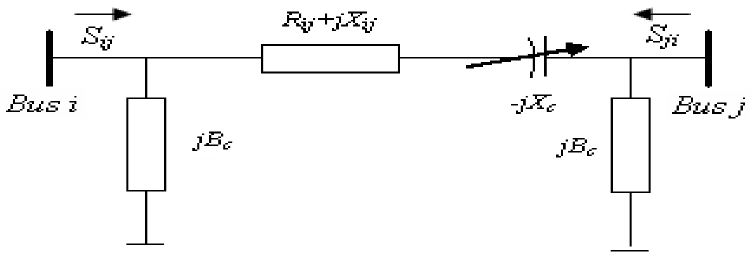

Figure 4.1: Model of a TCSC

The complex power flowing from bus i to bus j can be expressed as

$$S^*_{ij} = P_{ij} - jQ_{ij} = V_i^* I_{ij} \quad \textbf{(4.1)}$$

$$= V_i^2 \; [G_{ij} + j\,(B_{ij} + B_c)] - V_i^* V_j\,(G_{ij} + jB_{ij})$$

The active and reactive power loss in the line can be calculated as

$$P_L = P_{ij} + P_{ji}$$

$$P_L = V_i^2 G_{ij} + V_j^2 G_{ij} - 2\, V_i V_j \; G_{ij} \cos \delta_{ij} \quad \textbf{(4.2)}$$

$$Q_L = Q_{ij} + Q_{ji}$$

$$Q_L = -V_i^2(B_{ij} + B_c) - V_j^2(B_{ij} + B_c) + 2\, V_i V_j \; B_{ij} \cos(\delta_{ij}) \quad \textbf{(4.3)}$$

These equations are used to model the TCSC in the power flow formulations.

4.2. Static VAR Compensator (SVC) [1].

The static VAR compensator (SVC) is generally used as a voltage controller in power systems. It can help maintain the voltage magnitude at the bus it is connected to at a desired value during load variations. We can model the SVC as a variable reactive power source. Figure 4.2 shows the schematic diagram of a SVC.

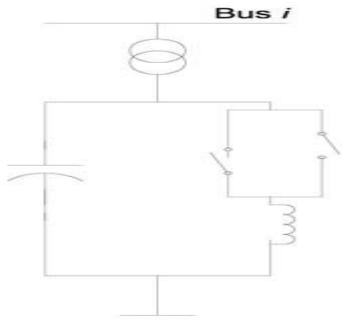

Figure 4.2: Schematic diagram of a SVC.

V and V_{ref} are the node and reference voltage magnitudes, respectively. Modeling the SVC as a variable VAR source, we can set the maximum and minimum limits on the reactive power output QSVC according to its available inductive and capacitive susceptances B_{ind} and B_{cap} , respectively. These limits can be given as

$$Q_{max} = B_{ind} \cdot V_{ref}^2 \quad (4.4)$$

$$Q_{min} = B_{cap} \cdot V_{ref}^2 \quad (4.5)$$

Where,

$$B_{ind} = \frac{1}{X_L} \text{ And } B_{cap} = \frac{1}{X_c}$$

V. OPTIMAL LOCATION BASED ON SENSITIVITY APPROACH FOR TCSC AND SVC DEVICES

We look at static considerations here for the placement of FACTS devices in the power system. The objectives for device placement may be one of the following:
1. Reduction in the real power loss of a particular line
2. Reduction in the total system real power loss
3. Reduction in the total system reactive power loss
4. Maximum relief of congestion in the system.
5. Increase in available transfer capability.

The Reduction of Total System Reactive Power Losses Sensitivity factors with respect to the parameters of TCSC and SVC are defined as, [17,21]

1. Loss sensitivity with respect to control parameter X_{ij} of TCSC placed between buses i and j,

$$a_{ij} = \frac{\partial Q_L}{\partial X_{ij}} \quad (5.1)$$

2. Loss sensitivity with respect to control parameter Q_i of SVC placed at bus i,

$$C_i = \frac{\partial QL}{\partial Qi} \quad (5.2)$$

These factors can be computed for a base case power flow solution. Consider a line connected between buses i and j and having a net series impedance of X_{ij} , that includes the reactance of a TCSC, if present, in that line. The loss sensitivities with respect to X_{ij} and Q_i can be computed as**:**

$$a_{ij} = \frac{\partial Q_L}{\partial X_{ij}} = \left[V_i^2 + V_j^2 - 2V_iV_j\cos(\delta_i - \delta_j)\right]\frac{R_{ij}^2 - X_{ij}^2}{(R_{ij}^2 + X_{ij}^2)^2} \quad (5.3)$$

$$C_i = \frac{\partial Q_L}{\partial Q_i} = \frac{2V_j}{\pi X_l}\left[\cos(2\alpha) - 1\right] \quad (5.4)$$

Where,
Vi is the voltage at bus i
Vj is the voltage at bus j
Rij is resistance of line connected between bus i and j
Xij is the reactance connected between bus i and j
α is the firing angle of SVC.

5.1. Criteria for placement of FACTS: [17]

The FACTS device must be placed on the most sensitive lines. With the sensitive indices computed for each type of FACTS devices, TCSC and SVC should be placed in the most positive line (K).

VI. SIMULATION AND RESULTS

The study has been conducted on an IEEE-14 bus system by using Power World Simulator Software. Power World Simulator is an interactive power systems simulation package designed to simulate high voltage power systems operation on a time frame ranging from several minutes to several days. The software contains a highly effective power flow analysis package capable of efficiently solving systems with up to 100,000 buses.

Where the single line diagram of the modified IEEE-14 bus system is shown in figure 6.1. The system is divided in to two areas, the buses1,2,6,11,12,13 belongs to area1 while the buses 3,4,5,7,8,9,10,14 belongs to area2. The ATC will be calculated between area 1 to area 2 and area 2 to 1. Base values are assumed to be 1000 MVA . The voltage limit is taken from 0.9 p.u to 1.1 p.u. This system has five generators and eleven loads.

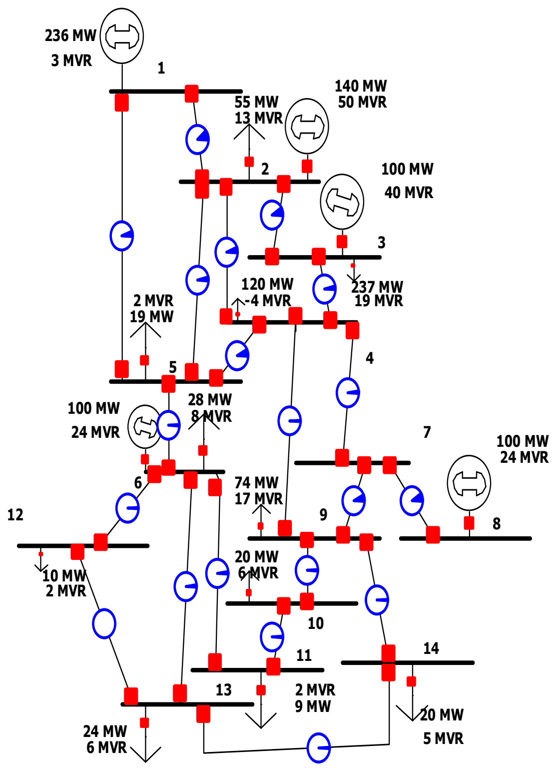

Figure 6.1: IEEE -14 bus system

The total Transfer Capability (TTC) of the limiting case from area 1 to area 2 is calculated as the 525MW by Repeated Power Flow method (RPF). In this regard ATC from area 1 to area 2 is calculated as ATC= TTC- Base Case Value, in which the base case value is equal to 490 MW, therefore ATC is equal to 35 MW. Similarly the ATC from area 2-1 is calculated as 66.6 MW, where TTC is 192.6 MW and base case value is 126 MW.
The TTC of a modified IEEE -14 bus system was examined under different situations and the results were tabulated in the table I.

Table I: Values of TTC of a modified 14-bus system under different situations.

Parameters		Area 1-2	Area 2-1
Base case	TTC(MW)	525	192.6
	Limiting factor	V14	V13
Contingency (line outage) (5-4)	TTC (MW)	508.6	173
	Limiting factor	V14	V11

The FACTS devices considered here are Thyristor Controlled Series Capacitor (TCSC) and Static VAR Compensator (SVC). Various sensitivity Methods are used to determine the optimal locations of FACTS devices to achieve different objectives. In this paper, the Reduction of Total System Reactive Power Losses method was used to determine the optimal placement of TCSC and SVC for TTC enhancement by RPF method. The sensitivity indices for TCSC at different compensation levels were tabulated in the table II.

Table II: sensitivity factors for TCSC at different compensation levels.

Line	From bus	To bus	Sensitivity index	
			TCSC (20%) (aij)	TCSC(30%) (aij)
1.	1	2	-1.0694	-0.9974
2.	1	5	-0.4429	-0.4773
3.	2	3	-0.7225	-0.9412
4.	2	4	-0.3400	-0.3485
5.	2	5	-0.1565	-0.1605
6.	3	4	-0.1502	-0.1412
7.	4	5	-0.5885	-0.5528
8.	4	7	-0.0626	-0.0670
9.	4	9	-0.0130	-0.0155
10.	5	6	-0.0058	-0.0071
11.	6	11	-0.0298	-0.0255
12.	6	12	-0.0106	-0.0086
13.	6	13	-0.0571	-0.0436
14.	7	8	-1.0242	-1.0223
15.	7	9	-0.7035	-0.7289
16.	9	10	-0.0062	-0.0055
17.	9	14	**-0.0049**	**-0.0041**
18.	10	11	-0.0147	-0.0126
19.	12	13	**-0.0004**	**-0.0007**
20.	13	14	-0.0095	-0.0076

The most positive sensitivity in the case of TCSC is presented bold type in the tabular form. The optimal placement of TCSC is in the line 17, 19 at different compensation levels. The TTC is calculated as 527.2MW when TCSC is placed in line 17, 19 and the line is compensated by 20% of its reactance. The ATC in this case is 37.2 MW from area1- 2.Similarly the TCSC is placed in line 17, 19 at compensation level of 30%, the TTC is calculated as 528.3MW from area 1 -2 and the corresponding value of ATC was calculated as 38.3 MW. Similarly the calculations have been carried out from area 2–1 also. The ATC values at different compensation levels of TCSC were tabulated below in the table III.

Table III: ATC values at different compensation levels of TCSC.

FROM TO AREA	ATC(MW) WITHOUT FACTS	ATC(MW) WITH FACTS TCSC(20%)	ATC(MW) WITH FACTS TCSC(30%)
1-2	**35**	**37. 2**	**38. 3**
2-1	**66. 6**	**67. 6**	**68**

The use of FACTS devices not only results in enhancement of ATC which in turn results in the increase of lodability of lines. The lodability of lines were tabulated in the table IV.

Table IV: Lodability of transmission lines at different compensation levels.

Line	From bus	To bus	Lodability of lines in MW.		
			BASE CASE	TCSC (20%)	TCSC (30%)
1.	1	2	152.87	154.87	155.78
2.	1	5	82.89	84	84.26
3.	2	3	106.13	106.60	106.82
4.	2	4	74.96	75.79	76.19
5.	2	5	52.75	53.29	53.54
6.	3	4	36.87	36.47	36.26
7.	4	5	93.23	94.40	95.02
8.	4	7	8.33	6.89	6.15
9.	4	9	15.52	16.35	16.78
10.	5	6	18.57	18.78	18.78
11.	6	11	26.41	37.35	27.85
12.	6	12	17.30	17.51	17.59
13.	6	13	46.85	45.94	45.35
14.	7	8	99.97	100	100
15.	7	9	91.64	93.10	93.85
16.	9	10	3.52	2.66	2.20
17.	9	14	29.65	32.79	34.43
18.	10	11	16.73	17.62	18.10
19.	12	13	6.92	7.13	7.20
20.	13	14	28.13	27.46	29.96

The plot which represents the lodabilty of transmission lines at different compensation levels were shown in figure 6.2 and figure 6.3. From the figures we can observe that placing TCSC in the most positive lines have increased the power carrying capability of most of the transmission lines.

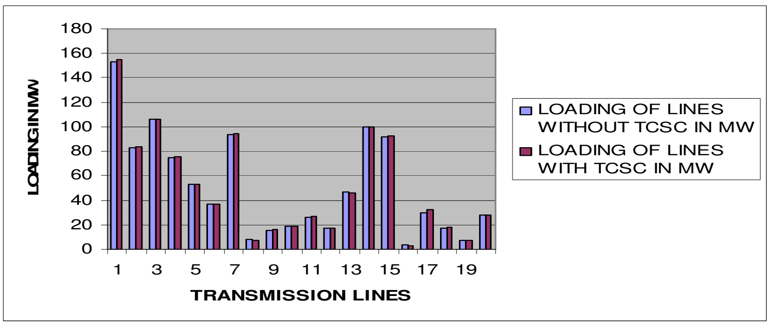

Figure:6.2 lodability of lines at 20% of compensation.

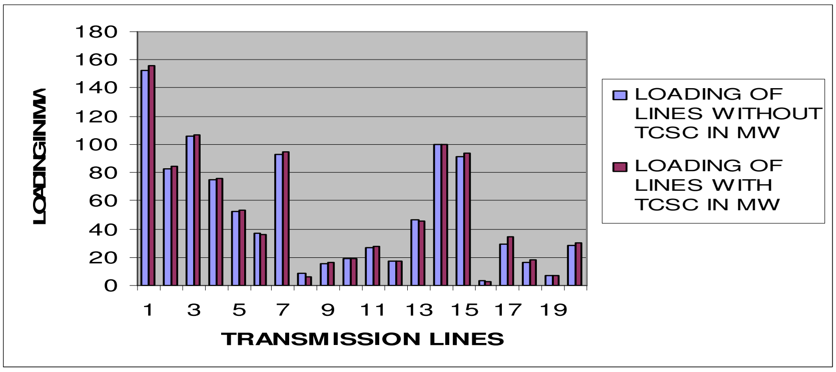

Figure:6.3:lodability of lines at 30% of compensation.

The sensitivity factors for Static VAR Compensator (SVC) of a modified IEEE-14 bus system bus were tabulated below table V. by taking firing angle of SVC as α as 15 degrees and Xl=20Ω.Most positive sensitivity factor occurs at bus 14 and therefore SVC is placed at bus 14 and a. reactive power of 30 MVAR is injected in to bus 14.

Before placing SVC lowest voltage appears at bus -14. Then the SVC from the table V. is placed at bus-14 which is most positive a reactive power of 30MVAR is injected at bus14. Then the lowest voltage in area 2 appears at bus-10 as 0.99671 p.u. The TTC value from area 1 to area 2 is calculated as 563 MW and therefore ATC is evaluated as 73MW as the base case load is 490MW.

Table V: Sensitivity factors of SVC for 9 bus system.

S.NO	BUS NO	Sensitivity index for SVC Ci
1.	1	-0.00479
2.	2	-0.00462
3.	3	-0.00379
4.	4	-0.00406
5.	5	-0.00423
6.	6	-0.00410
7.	7	-0.00401
8.	8	-0.00435
9.	9	-0.00367
10.	10	-0.00359
11.	11	-0.00381
12.	12	-0.00383
13.	13	-0.00374
14.	14	**-0.00343**

Similarly the TTC from area 2-1 is calculated as 202.2MW and therefore ATC is evaluated as 76.2MW as the base case load is 126 MW with V13 as limiting factor. The effect of SVC on the TTC is demonstrated through a modified IEEE-14 bus system. SVC can improve TTC. It is shown that installing SVC as a FACTS device will improve voltage profile as well as resulting TTC enhancement.

The voltage profiles of modified IEEE-14 bus system without and with SVC were tabulated in the table VI. Voltage profiles of a modified IEEE-14 bus system without and with SVC are shown in figure 6.4:

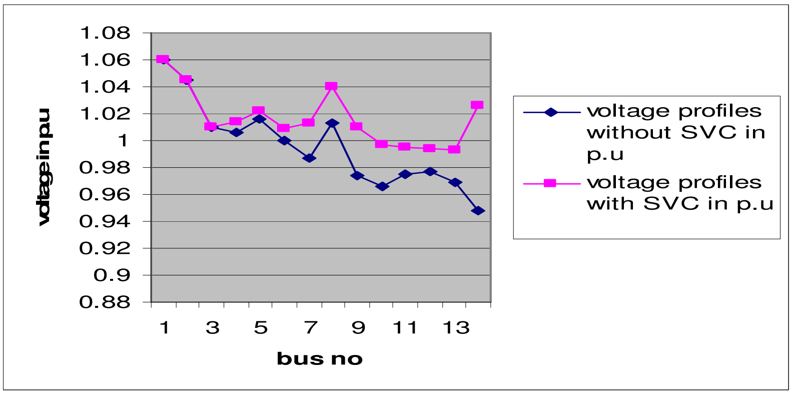

Figure 6.4: voltage profiles of a nine bus system without and with SVC.

Table VI: voltage profiles of modified IEEE-14 Bus system with and without SVC.

S.NO	BUS NO	VOLTAGE PROFILE WITHOUT SVC (P.U)	VOLTAGE PROFILE WITH SVC (P.U)
1.	1	1.0600	1.0600
2.	2	1.0450	1.0450
3.	3	1.0100	1.0100
4.	4	1.0062	1.0140
5.	5	1.0159	1.0218
6.	6	1.0000	1.0089
7.	7	0.9867	1.0131
8.	8	1.0130	1.0395
9.	9	0.9745	1.0095
10.	10	0.9659	0.9967
11.	11	0.9749	0.9951
12.	12	0.9770	0.9945
13.	13	0.9688	0.9934
14.	14	0.9478	1.0263

VII. CONCLUSION

In this paper as described a simple efficient method for determining the ATC with and without FACTS devices has been examined. A sensitivity based approach has been developed for finding the optimal placement of FACTS devices in a deregulated market having pool and bilateral dispatches. In this system first the few locations of FACTS devices can be decided based on a_{ij} and c_i and the optimal dispatch problem is solved to select the optimal location and parameter settings. From the results it is shown that installing SVC as a FACTS device will improve the voltage profile as well as resulting ATC enhancement, where as TCSC can improve ATC in both thermal domain case and voltage domain case at different compensation levels.

VIII. FUTURE SCOPE

The usage of neural networks can be implemented to improve the maintenance and tracking of real power being transferred in a power system grid. With its implementation, not only would it facilitate the system operator's job but it would also provide a convenient and faster method of calculation and a more reliable way of preventing blackouts or power overload. This can be extended to online applications.

The challenge for engineers is to produce and provide electrical energy to consumers in a safe, economical and reliable manner under various constraints. Many more accurate models to be developed to predict better how a realistic power system will react over a wide range of operating conditions. This kind of models will also help in the further research of ATC.

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