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Transmission Congestion and Voltage Profile Management Using TCSC and TCPAR in Deregulated Power System

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Abstract
In present days all our basic needs are relates with electricity. As the population increases, the demand for electricity is also tremendously increases. In the past, the entire electricity industry is under the control of government and also monopolized. But now, the power industry in many countries is moving rapidly from regulated conventional setup to deregulated environment. The transmission congestion is one of the technical problems that particularly appear in the deregulated power system. If congestion is not managed we face the problems of electricity price improvement and security and stability problems. Congestion relief can be handled using FACTS device such as TCSC, TCPAR where transmission capability will be improved. These FACTS devices are optimally placed on transmission system using Sensitivity approach method. The proposed method is carried out on Modified IEEE-14 bus system and IEEE-24 bus system Using Power World Simulator17 software.
Keywords*:* Deregulated power system, TCSC, TCPAR

I. Introduction

The dependency on the electrical energy is increased due to the rapid growth in the industrialization sector and urbanization of life style. This has resulted into demand for electricity increases. To meet the growing power demand, electric supply industry has to adopt the deregulated structure. In deregulation environment generation, transmission and distribution are independent activities. The power system deregulation is expected to offer the benefit of lower electricity price, better consumer service and improved system efficiency [1].

Congestion in a transmission network is one of the technical problems. Transmission congestion may be defined as the condition where more power is scheduled (or) flows across transmission lines and transformers than the physical limits of the lines and transformer. Congestion management is very essential in deregulated power system because transmission congestion occurs due to line outages, higher load demand. If congestion is not managed, we face problem of electricity charges increases, reliability, and stability of system [2].The objective of the congestion management is to take actions (or) control measures in relieving congestion of transmission network and increasing the power transferring capabilities. It can be reduced without disturbing the economy of the system. Some corrective measure such as outages of congested branches using FACTS devices is employed.

To relieve the congestion ISO can use mainly two types of techniques which are as follows: [1]

A. Cost free means:
Out-ageing of congested lines.
- Operation of transformer taps/phase shifter.
- Operation of FACTS devices particularly series devices.

B Non-Cost free means:
- Re-dispatching the generation amounts. By using this method, some generators back down while others increase their output. The effect of re-dispatching is that generators no longer operate at equal incremental costs.
- Curtailment of loads and the exercise of load interruption options.

In [3] 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 system. [5]FACTS devices makes it possible to use circuit reactance, voltage magnitude, and phase angle as controls to redistribute line flow and regulate voltage profile. Flexible AC Transmission Systems (FACTS), provide proven technical solutions to address these new operating challenges being presented today. Thyristor Controlled Series Capacitor (TCSC), Thyristor Controlled Phase Angle Regulator (TCPAR) are used for relieve congestion using Sensitivity based methods.

II. THYRISTOR CONTROLLED SERIES COMPENSATOR (TCSC)

[4]Thyristor controlled series compensator (TCSC) are connected in series with transmission lines. It is equivalent to a controllable reactance inserted in series with a line to compensate the effect

of the line inductance. The net transfer reactance is reduced and leads to an increase in power transfer capability.

[7]The basic structure of TCSC, shown in Figure 3

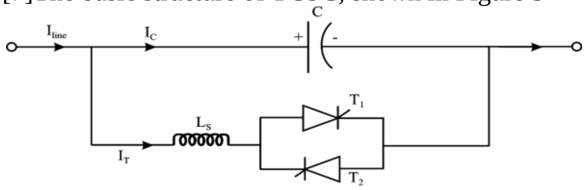


Fig1.Basic structure of THYRISTOR CONTROLLED SERIES CAPACITOR

2.1 Modeling of TCSC:

[6]The transmission line model with a TCSC connected between the two buses *i* and *j* is shown in Figure 5. Equivalent *Π* model is used to represent the transmission line. TCSC can be considered as a static reactance of magnitude equivalent to *-jXc*. The controllable reactance *Xc* is directly used as control variable to be implemented in power flow equation.

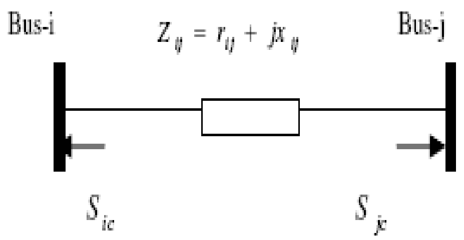


Fig2. Injection Model of TCSC

[8]The following equations are used to model TCSC. Let the voltages at bus *i* and bus *j* are represented by $V_i \angle \delta_i$ and $V_j \angle \delta_j$. The complex power from bus *i* to *j* is

$$S_{ij}^* = P_{ij} - Q_{ij} = V_i^* I_{ij}$$
$$= \left[\left(V_i - V_j\right)Y_{ij} + V_i(jB_c)\right]$$
$$= V_i^*\{\left[G_{ij} + j\left(B_{ij} + B_c\right)\right] - V_i^* V_j\left(G_{ij} + jB_{ij}\right\}$$
$$G_{ij} + jB_{ij} = \frac{1}{R_L + jX_L - jX_c}$$

From the above equations the real and reactive power equations can be written as

$$P_{ij} = V_i^2 G_{ij} - V_i V_j G_{ij}\cos(\delta_i - \delta_j) - V_i V_j B_{ij}\sin\left(\delta_i - \delta_j\right)$$
$$Q_{ij} = -V_i^2\left(B_{ij} + B_c\right) - V_i V_j G_{ij}\sin\left(\delta_i - \delta_j\right) + V_i V_j B_{ij}\cos\left(\delta_i - \delta_j\right)$$

III. STATIC MODELING OFTHYRISTOR CONTROLLED PHASE ANGLE REGULATOR (TCPAR)

The basic [13] structure of a TCPAR is given in Figure-9. The shunt connected transformer draw power from the network then provide it to the series connected transformer in order to introduce a injection voltage at the series branch. Compare to conventional phase shifting transformer, the mechanical tap changer is replaced by the thyristor controlled unit.

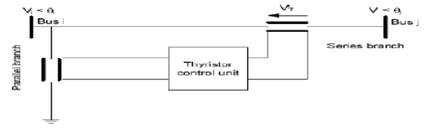


Figure 3 Basic structure of TCPAR

2.2.3 Mathematical calculations of TCPAR:

TCPAR [12] can be modeled by phase shifting transformer with control parameter a α .Figure-4 shows the model of TCPAR. The static model of a TCPAR having a complex tap ratio of 1:a∠ α and a transmission line between bus i and bus j is shown in Figure-4.5.1

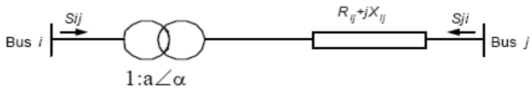


Figure 4 Model of TCPAR

The real and reactive power flows from bus *i* to bus *j* can be expressed as

$$P_{ij} = Re\{V_i^*[(a2V_i - a^*V_j)Y_{ij}]\} = a2V2iG_{ij} - aV_iV_jG_{ij}\cos\left(\delta_i - \delta_j + \alpha\right) - aV_iV_jB_{ij}\sin(\delta_i - \delta_j + \alpha)$$ and

$$Q_{ij} = -Im\{Vi^*[(a2Vi - a^*Vj)Y_{ij}]\} = -a2Vi2G_{ij} - aViVjB_{ij}\cos\left(\delta_i - \delta_j + \alpha\right) - aViVjG_{ij}\sin(\delta_i - \delta_j + \alpha)($$

Similarly, real and reactive power flows from bus *j* to bus *i* can be written as

$$P_{ij} = Re\{V_j^*[(V_j - aV_i)Y_{ij}]\} = Vj2G_{ij} - aViVjG_{ij}\cos(\delta i - \delta j + \alpha) + aViVjB_{ij}\sin(\delta i - \delta j + \alpha)$$ And

$$Q_{ji} = -Im\{V^*j[(Vj - aVi)Y_{ij}]\} = -V2jB_{ij} + aViVjB_{ij}\cos(\delta i - \delta j + \alpha) + aViVjG_{ij}\sin(\delta i - \delta j + \alpha)($$

The real and reactive power loss in the line having a TCPAR can be expressed as:

$$P1 = P_{ij} + P_{ji} = a2Vi2G_{ij} + Vj2G_{ij} - 2ViVjG_{ij}\cos(\delta i - \delta j + \alpha)$$
$$Q1 = Q_{ij} + Q_{ji} = -a2Vi2G_{ij} - Vj2B_{ij} + 2aViVjB_{ij}\cos(\delta i - \delta j + \alpha)\ ($$

These equations will be used to model the TCPAR in the power flow formulation. The injection model of the TCPAR is shown as follows

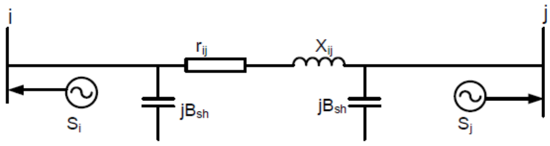


Fig5. Injection model of TCPAR

The TCPAR grants an efficient ability to reduce losses, control steady-state power flow, and efficiently and flexibly maximize line utilization and consequently can increase system capability and improve reliability. The TCPAR can change the relative phase angle between the system voltages. Therefore, can control the real power flow in transmission lines in order to remove congestion, mitigate the frequency oscillations and enhance power system stability.

IV. SENSITIVITY APPROACH FOR OPTIMAL LOCATION OF TCSC AND TCPAR

Generally, [4] the location of FACTS devices depends on the objective of the installation. The reactive power loss sensitivity factors with respect to these control variables may be given as follows:

1. Loss sensitivity with respect to control parameter Xij of TCSC placed between buses i and j,

$$\mathbf{a_{ij}}=\frac{\partial QL}{\partial X_{ij}}=[V_i^2+V_j^2-2V_iV_j\cos(\delta_i-\delta_j)]\frac{R_{ij}^2-X_{ij}^2}{(R_{ij}^2+X_{ij}^2)^2}$$

,

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

2. Loss sensitivity with respect to control Parameter θij of TCPAR placed between buses i and j,

$$b_{ij}=\frac{\partial Q_L}{\partial\theta_{ij}}=\left[-2\alpha V_iV_jB_{ij}\sin\theta_{ij}\right]$$

The FACTS device must be placed on the most sensitive lines. With the sensitive indices computed for each type of FACTS device, TCSC, TCPAR should be placed in a line (K) having most positive value and absolute value of sensitivity respectively.

V. Simulation and results discussion:

The study has been conducted on transmission congestion management of an IEEE 14 BUS system and IEEE 24 BUS systems using power world simulator 17.0.

For each system the transmission congestion management is determined by placing different FACTS devices like TCSC, TCPAR in the optimal location using sensitivity approach method.

The two systems are modeled internally using power world simulator. The following section contains detailed results.

Case study-1: IEEE 14 BUS SYSTEM

This system consists of 14 buses, 17 line sections, 5 generator buses and 8 load buses

Fig1.Single line diagram of IEEE 14 bus system

The percentage loadability of IEEE 14 bus system is as follows

LINES	FROM BUS	TO BUS	LODABILITY%	LINES	FROM BUS	TO BUS	LODABILITY %
1	1	2	47	11	6	11	74
2	1	5	34	12	6	12	67
3	2	3	73	13	6	13	74
4	2	4	14	14	7	8	34
5	2	5	19	15	7	9	61
6	3	4	15	16	9	10	38
7	4	5	79	17	9	14	33
8	4	7	23	18	10	11	64
9	4	9	26	19	12	13	13
10	5	6	**82**	20	13	14	78

Table1.Opf results of modified IEEE 14 bus system

The line 5-6 is ready to congest. Due to the increased loading the line is congest.

By using TCSC the congestion is going to be alleviated. For placing TCSC at optimal location, we use sensitivity analysis. The sensitivity indices table of modified IEEE 14 bus system is shown below.

LINE	FROM BUS	TO BUS	SENSITIVITY INDEX(a_{ij})	LINE	FROM BUS	TO BUS	SENSITIVITY INDEX (a_{ij})
1	1	2	1.0718	11	6	11	1.6356
2	1	5	0.1126	12	6	12	0.1479
3	2	3	0.1558	13	6	13	0.5998
4	2	4	0.0075	14	7	8	-0.2928
5	2	5	0.0261	15	7	9	-0.9513
6	3	4	0.036	16	9	10	0.0523
7	4	5	**2.1023**	17	9	14	0.0129
8	4	7	-0.385	18	10	11	0.0753
9	4	9	-0.172	19	12	13	0.1140
10	5	6	-7.248	20	13	14	0.1459

Table2.Sensitivity indexes for modified IEEE 14 bus system

From the above table 2, the line 4-5have the most positive sensitivity factors. So this is the best locations for placement of TCSC to relieve congestion in the network. By placing the TCSC in line 4-5, the congestion in the network is relieved.

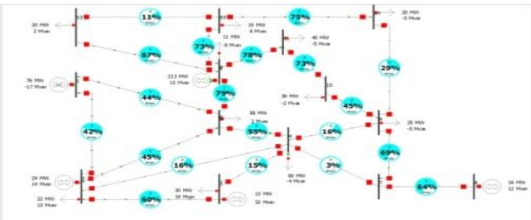


Fig2.Modified IEEE 14 bus system with TCSC in line 4-5

The fig 2 shows the transmission line flows with TCSC. It is observed that after placing TCSC the congestion in the network is relieved.

The cost function values of system before and after placing TCSC are as follows

Cost function value	Without TCSC	With TCSC 20% compensation	With TCSC 50% compensation	With TCSC 60% compensation
Initial cost value	4276.75 $/hr	3763.36 $/hr	3937.56 $/hr	3936.01 $/hr
Final cost value	4276.75 $/h	3756.36 $/h	3922.56 $/h	3936.01 $/h
total cost	4276.75$/h	3756.36 $/h	3922.56 $/h	3936.01 $/h

Table3.cost function values of modified IEEE 14 bus system with and without TCSC

The congestion cost function values of modified IEEE-14 bus system with and without TCSC are shown in below

marginal cost	Without TCSC	Congestion cost	20% Compensation	Congestion Cost	50% Compensation	Congestion Cost	60% Compensation	Congestion cost
High cost	16.5	4.31	12.4	0	13.2	0	13.4	0
Low Cost	10.5	-1.6	12.4	0	13.2	0	13.46	0
Avg cost	13.67	0.23	12.4	0	13.20	0	13.4	0

Table4.congestion cost values of modified IEEE-14 bus system with and without TCSC

In modified IEEE-14 bus system before installing TCSC the customer face the congestion cost value is 16.50$/MWH, after placing TCSC the congestion cost value is 0.

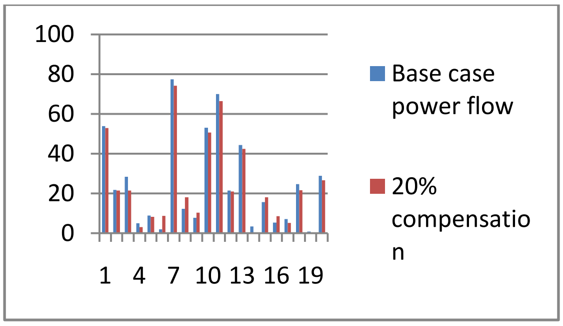
The list of power flows with and without TCSC is listed below as follows

Lines	From bus	To bus	Without TCSC	With TCSC 20% compensation	With TCSC 50% compensation	With TCSC 60% compensation
1	1	2	53.8	52.9	54	53.9
2	1	5	21.7	21.4	21.9	21.9
3	2	3	28.4	21.5	28.4	28.4
4	2	4	5	3	5	5
5	2	5	8.8	8.3	9	8.9
6	3	4	2	8.7	2	2
7	4	5	77.4	74.2	75.9	76.3

8	4	7	12.3	18	11.4	11.6
9	4	9	7.7	10.3	7.1	7.2
10	5	6	53.1	50.6	51.1	51.5
11	6	11	70	66.4	73	72.4
12	6	12	21.4	20.9	21.3	21.3
13	6	13	44.3	42.5	43.6	43.8
14	7	8	3.4	0	3.2	3.2
15	7	9	15.6	18	14.6	14.8
16	9	10	5.4	8.5	3.1	3.5
17	9	14	7.1	5.1	6.4	6.5
18	10	11	24.7	21.6	27	26.5
19	12	13	0.8	0.4	0.7	0.7
20	13	14	28.9	26.6	28.1	28.2

Table5. Power flow list of modified IEEE 14 bus system with and without TCSC

The Comparison of power flows with and without TCSC is shown as

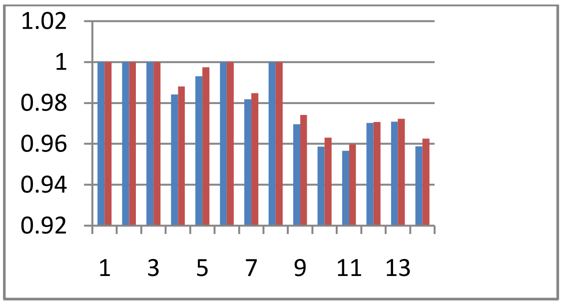


Power flow comparison with 20% compensation

Comparison of voltage profiles with and without TCSC as follows

Buses	Without TCSC	With TCSC (20% compensation)	Buses	Without TCSC	with TCSC(20% compensation)
1	1	1	8	1.0000	1
2	1	1	9	0.9696	0.97413
3	1	1	10	0.9585	0.96297
4	0.98412	0.98808	11	0.9565	0.95981
5	0.99301	0.99741	12	0.9702	0.97065
6	1.00001	1	13	0.9709	0.97223
7	0.98182	0.98478	14	0.9587	0.96253

Table6.Voltage profile list with and without TCSC for modified IEEE-14 bus system.



Voltage profile comparison with 20% compensation

The transmission congestion in IEEE 14 bus system is also alleviated by using TCPAR.TCPAR is placed with a phase shift of 1 and unity tap ratio. For placing TCPAR at optimal location, we use sensitivity analysis.
The sensitivity indices table of modified IEEE 14 bus system is shown below.

Line	From bus To bus	Sensitivity indices		
		20% compensation	30% compensation	40% compensation
1	1-2	-0.0037	-0.0056	-0.0074
2	1-5	-0.0043	-0.0065	0.0087
3	2-3	-0.0058	-0.0066	-0.0088
4	2-4	-0.0047	-0.0054	-0.0094
5	2-5	-0.181312	-0.0015	-0.002
6	3-4	0.128438	0.0011	0.0014
7	4-5	**0.15591**	**0.0013**	**0.0017**

Table7. Sensitive indexes for modified IEEE-14 bus system with TCPAR

From the above table 7, the line 4-5have the most positive sensitivity factors. So this is the best locations for placement of TCPAR to relieve congestion in the network. By placing the TCPAR in line 4-5, the congestion in the network is relieved.

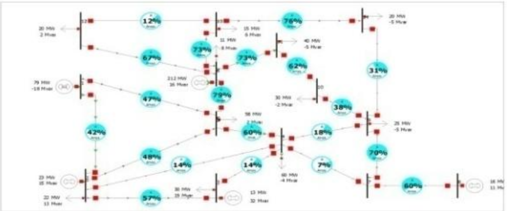


Fig3. Modified IEEE 14 bus system with TCPAR in line 4-5

The fig 3 shows the transmission line flows with TCPAR. It is observed that after placing TCPAR the congestion in the network is relieved.

The cost function values of system with and without TCPAR

Cost function value	Without TCPAR	With TCPAR		
		20% compensation	50% compensation	60% compensation
Initial cost value	4276.75 $/hr	3946.26$/hr	3944.52 $/hr	3937.33 $/hr
Final cost value	4276.75 $/h	3946.27$/h	3945.09 $/h	3937.38 $/h
final total cost value	4276.75 $/h	3946.27$/h	3945.09 $/h	3937.38 $/h

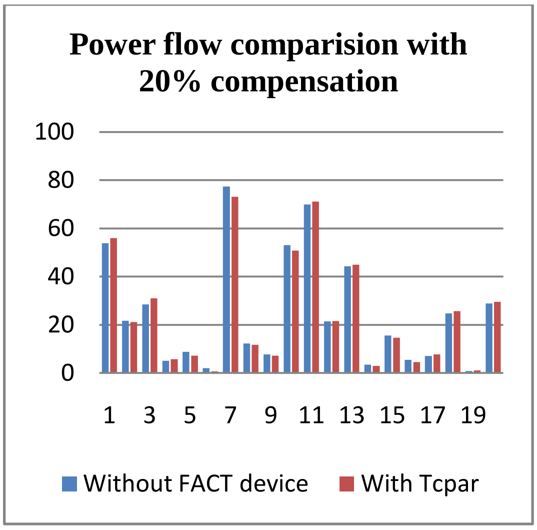
Table8.Cost function value with and without TCPAR

The congestion cost values of IEEE-14 bus system with and without TCPAR

Table9.Congestion cost values with and without TCPAR of modified IEEE-14 bus

The Comparison of power flows with and without TCPAR is shown as

marginal cost	Without TCSC($/MWH)	Congestion cost ($/MWH)	20% Compensation	Congestion cost	50% Compensation	Congestion Cost	60% Compensation	Congestion cost
High cost	16.5	4.31	12.4	0	13.2	0	13.2	0
Low Cost	10.5	-1.6	12.4	0	13.20	0	13.2	0
Avg cost	13.67	0.23	12.4	0	13.20	0	13.2	0

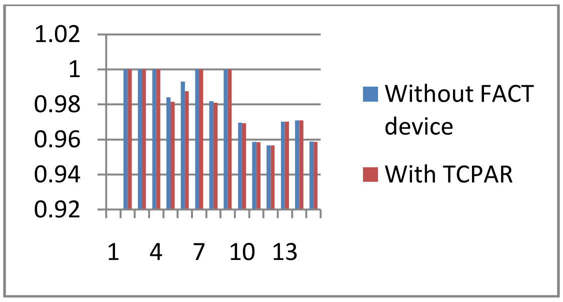


Comparison of voltage profiles with and without TCPAR as

Buses	Without TCPAR	With TCPAR (20% compensation)	Buses	Without TCPAR	with TCPAR(20% compensation)
1	1	1	8	1.00001	1.00001
2	1	1	9	0.9696	0.96837
3	1	1	10	0.95859	0.95737

4	0.9841	0.9834	11	0.956	0.9555
	0.9930	0.9925	12	0.970	0.9700
6	1.00001	1	13	0.97091	0.97501
7	0.98182	0.9811	14	0.958	0.9756

Table10. Voltage profile list with and without TCPAR



Voltage profile comparison with 20% compensation

Case study-2: IEEE 24 BUS SYSTEM

This system consists of 24 buses, 37 line sections, 10 generator buses and 17 load buses.

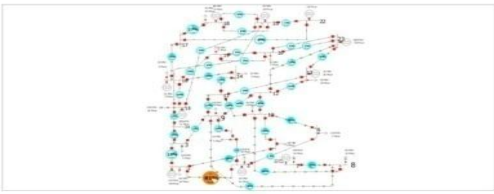


Fig4. Single line diagram of modified IEEE-24 bus system

The percentage loadability of IEEE 24 bus system is as follows

Line s	From bus	To bus	Lod ability%	Line s	From bus	To bus	Lod ability%
1	1	2	**81**	20	12	23	23
2	1	3	15	21	13	23	20
3	1	5	65	22	14	16	33
4	2	4	30	23	15	16	10
5	2	6	21	24	15	21	6
6	3	9	30	25	15	21	6
7	3	24	37	26	15	24	29
8	4	9	24	27	16	17	33
9	5	10	30	28	16	19	8
10	6	10	69	29	17	18	27
11	7	8	73	30	17	22	6
12	8	9	28	31	18	21	8
13	8	10	55	32	18	21	8
14	9	11	17	33	19	20	3
15	9	12	16	34	19	20	3
16	10	11	26	35	20	23	2
17	11	13	9	36	20	23	2
18	11	14	27	37	21	22	1
19	12	13	11	38	21	22	1

Table11. OPF results of modified IEEE-24 bus system

The line 1-2 is ready to congest. Due to the increased loading the line is congest. By using TCSC the congestion is going to be alleviated. For placing TCSC at optimal location, we use sensitivity analysis. The sensitivity indices table of modified IEEE 24 bus system is shown below.

Line	From bus	To bus	Sensitivity indexes		
			20% compensation	30% compensation	40% compensation
1	1	2	-1.2248	-0.0955	-0.1619
2	1	3	0.0434	-0.0012	-0.0548
3	1	5	0.5372	-0.0727	-0.692
4	2	4	0.1364	-0.0366	-0.1672
5	2	6	0.1437	0.029	0.1324
6	3	9	0.1648	-0.0505	-0.1875
7	3	24	-3.2093	-0.0541	-2.9515
8	4	9	0.065	-0.0038	-0.1132
9	5	10	0.1186	-0.0099	-0.1505
10	6	10	**1.2459**	**0.0819**	**0.7141**
11	7	8	0.5542	-0.0069	-0.7515

12	8	9	0.74	-0.0353	-0.9572
13	8	10	0.5462	-0.0266	-0.6988
14	9	11	-1.3131	-0.1136	-0.9857
15	9	12	-1.0781	-0.0709	-0.817
16	10	11	-2.1046	-0.2273	-2.121
17	11	13	-2.5151	-0.1685	-1.8903
18	11	14	-0.2065	-0.0264	-0.2917
19	12	13	-1.2304	-0.26	-2.0282
20	12	23	-0.2643	-0.031	-0.3823
21	13	23	-1.7474	-0.2085	-2.3489
22	14	16	-1.7278	-0.2025	-1.8897
23	15	16	-1.7933	-0.645	-2.9748
24	15	21	-1.5041	-0.5978	-0.8111
25	15	21	-0.1266	-0.06	0.3435
26	15	24	-0.1266	-0.06	0.4464
27	16	17	-1.2402	-0.3049	-2.1542
28	16	19	-1.5568	-1.3962	-2.6512
29	17	18	-0.1077	-19.08	-0.1557
30	17	22	-6.2192	-37.73	-1.7404
31	18	21	-0.14	-0.1234	-0.158
32	18	21	-0.2775	-1.5872	-0.3216
33	19	20	-0.2775	-1.5872	-0.3216
34	19	20	-0.0218	-0.072	-0.0308
35	20	23	-0.0218	-0.072	-0.0308
36	20	23	-0.0107	-0.0113	-0.0156
37	21	22	-0.0107	-0.0113	-0.0156

Table12. Sensitive indexes for modified IEEE-14 bus system with TCSC.

From the above table 12, the line 6-10have the most positive sensitivity factors. So this is the best locations for placement of TCSC to relieve congestion in the network. By placing the TCSC in line 6-10, the congestion in the network is relieved.

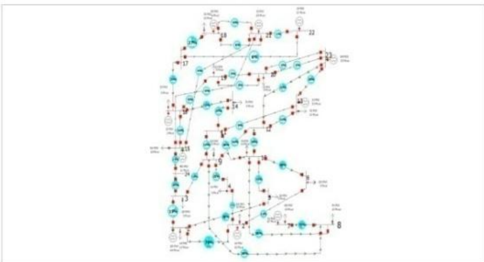


Fig5. Modified IEEE 24 bus system with TCSC in line 6-10

The fig 5 shows the transmission line flows with TCSC. It is observed that after placing TCSC the congestion in the network is relieved.

The cost function values of IEEE-24 bus system with and without TCSC as follows

Cost function value	**Without TCSC**	**With TCSC**		
		20% compensation	**50% compensation**	**60% compensation**
Initial cost value	54344.45$/hr	51888.01 $/hr	51891.63 $/hr	51895.41 $/hr
Final cost value	54344.45$/h	51888.01 $/h	51891.63 $/h	51895.41 $/h
final total cost value	54344.45$/h	51888.01 $/h	51891.63 $/h	51895.41 $/h

Table13.cost function values of modified IEEE-24 bus system with and without TCSC

The congestion cost values of system without TCSC

marginal cost	**Without TCSC($/MWH)**	**Congestion cost ($/MWH)**	**20% Compensation**	**Congestion cost**	**50% Compensation**	**Congestion Cost**	**60% Compensation**	**Congestion cost**
High cost	43	32.1	19.6	0	19.2	0	19	0
Low cost	13	0	19.6	0	19.2	0	19	0
Avg cost	23	10.4	19.6	0	19.2	0	19	0

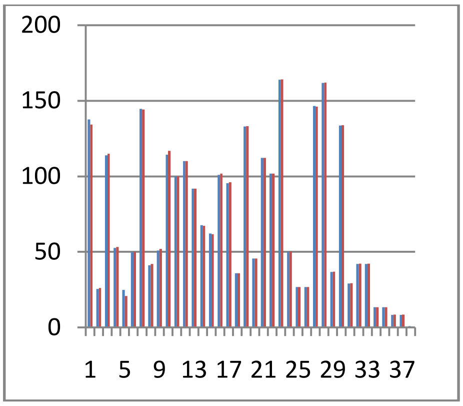
Table14. Congestion cost values with and without TCSC

The congestion cost value before installing TCSC is 43.3$/MWH after placing TCSC the congestion cost value is 0 $/MWH.
The list of power flows in the system with and without TCSC as follows

Lines	**From-to bus**	**Without TCSC**	**With TCSC**	
			20% compensation	**30% compensation**
1	1-2	137.67	134.3	134.7
2	1-3	25.53	26.1	26.1
3	1-5	113.81	115	114.9
4	2-4	52.62	53.3	53.2
5	2-6	24.87	20.8	21.2
6	3-9	49.86	50.1	50.1
7	3-24	144.68	144.3	144.4
8	4-9	41.69	41.9	41.8
9	5-10	50.9	52	51.9
10	6-10	111	116.9	116.6
11	7-8	100	1001	100
12	8-9	104.7	110.1	110.1
13	8-10	87.92	91.8	91.8
14	9-11	67.73	67.3	67.3
15	9-12	62.17	61.7	61.7
16	10-11	100.74	101.7	101.6
17	10-12	95.27	96.1	96.1
18	11-13	35.9	35.9	35.9
19	11-14	132.94	133.1	133.1
20	12-13	45.64	45.7	45.7
21	12-23	112.99	112.2	112.2
22	13-23	101.81	101.8	101.8
23	14-16	163.87	164.1	164.1
24	15-16	50.05	50.2	50.1
25	15-21	26.68	26.8	26.8
26	15-21	26.68	26.8	26.8
27	15-24	146.58	146.2	146.3
28	16-17	161.88	162.1	162.1
29	16-19	36.71	36.8	36.8
30	17-18	133.59	133.8	133.8
31	17-22	29.14	29.2	29.2
32	18-21	41.96	42.1	42
33	18-21	41.96	42.1	42
34	19-20	13.33	13.4	13.4
35	19-20	13.33	13.4	13.4
36	20-23	8.32	8.4	8.4
37	20-23	8.32	8.4	8.4
38	21-22	0.76	0.7	0.7

Table 15.Powerflow list with and without TCSC

The power flow comparison with and without FACTS device as follows



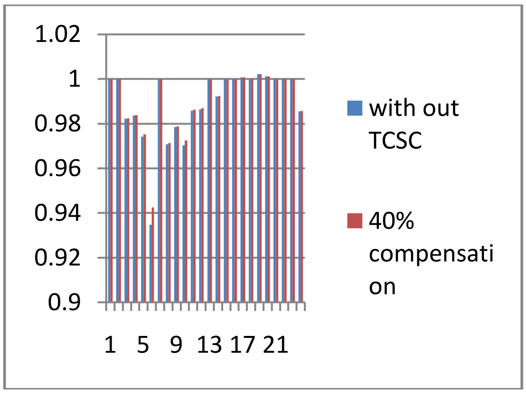
Power flow comparison with 20% compensation

The comparison of voltage profile with and without FACT device as

Buses	**Without TCSC**	**With TCSC (40% compensation)**	**Buses**	**Without TCSC**	**With TCSC (40% compensation)**
1	1	1	13	1	1
2	1	1	14	0.9922	0.9924
3	0.9822	0.9824	15	1	1
4	0.9837	0.9838	16	1	1
5	0.9742	0.9752	17	1.0008	1.0008
6	0.9347	0.9425	18	1	1
7	1	1	19	1.0021	1.0021
8	0.9707	0.9713	20	1.0012	1.0012
9	0.9785	0.9789	21	1	1
10	0.970.	0.9725	22	1	1
11	0.9858	0.9863	23	1	1
12	0.9865	0.987	24	0.9856	0.9856

Table16. Voltage profile list with and without TCSC

Voltage profile comparison with and without FACTS device as follows



Voltage profile comparison with and without FACT device for IEEE-24 bus system

The transmission congestion in IEEE 24 bus system is also alleviated by using TCPAR.TCPAR is placed with a phase shift of 3 and unity tap ratio. For placing TCPAR at optimal location, we use sensitivity analysis.

Line	**From bus**	**To bus**	**Sensitivity indexes**	
			20% compensation	**30% compensation**
1	1	2	-0.0146	-0.02198
2	1	3	-0.0129	-0.0193
3	1	5	-0.0093	-0.014
4	2	4	-0.0098	-0.0147
5	2	6	-0.0374	-0.0561
6	3	9	-0.0085	-0.0128
7	3	24	0	-0.0077
8	4	9	-0.0052	-0.0071
9	5	10	-0.0047	0.025
10	6	10	0.0167	0.0079
11	7	8	0.0053	0.0536
12	8	9	0.0357	0.0453
13	8	10	0.0302	0.009
14	9	11	0	0
15	9	12	0	0
16	10	11	0	0
17	11	13	0.0006	0.0289
18	11	14	0.0188	0.0118
19	12	13	0.0079	0.0671
20	12	23	**0.0865**	**0.1290**
21	13	23	0.0629	0.0423
22	14	16	0.0201	0.0134
23	15	16	-0.0121	-0.0522
24	15	21	-0.0056	-0.008
25	15	21	-0.0302	-0.0453
26	15	24	-0.0302	0.0134
27	16	17	0.0089	-0.0025
28	16	19	-0.0017	0.0034
29	17	18	0.0023	0.0397
30	17	22	0.0265	0.0036
31	18	21	0.0024	0.0036
32	18	21	0.0024	-0.0025
33	19	20	-0.0017	-0.0025
34	19	20	-0.0017	-0.0025
35	20	23	-0.05684	-0.08516
36	20	23	-0.05684	-0.08516
37	21	22	0.05301	0.078658
38	21	22	0.05301	0.078658

Table17. Sensitive indexes for modified IEEE-14 bus System with TCPAR.

The sensitivity indices table of modified IEEE 24 bus system is shown above.

From the above table 17, the line 12-23have the most positive sensitivity factors. So this is the best locations for placement of TCPAR to relieve congestion in the network. By placing the TCPAR in line 12-23, the congestion in the network is relieved.

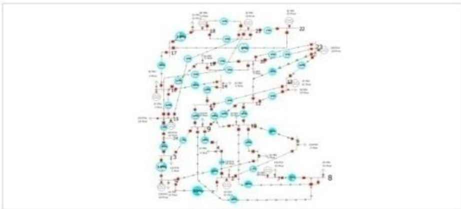


Fig6. Modified IEEE 24 bus system with TCPAR in line 12-23

The fig 4 shows the transmission line flows with TCPAR. It is observed that after placing TCPAR the congestion in the network is relieved.

The congestion cost value of modified system with and without TCSC is as follows

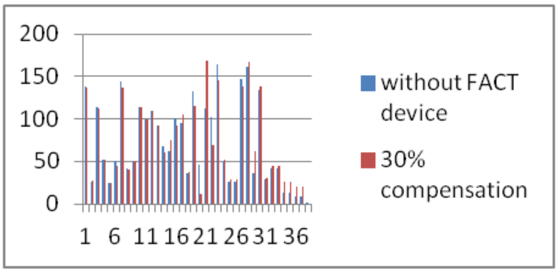
marginal cost	**Without TCSC($/MWH)**	**Congestion cost ($/MWH)**	**20% Compensation**	**Congestion cost**	**50% Compensation**	**Congestion Cost**	**60% Compensation**	**Congestion cost**
High cost	43	32.1	9.6	0	19.2	0	19	0
Low cost	13	0	19.6	0	19.2	0	19	0
Avg cost	23	10.4	19.6	0	19.2	0	19	0

Table18.congestion cost values with and without TCPAR

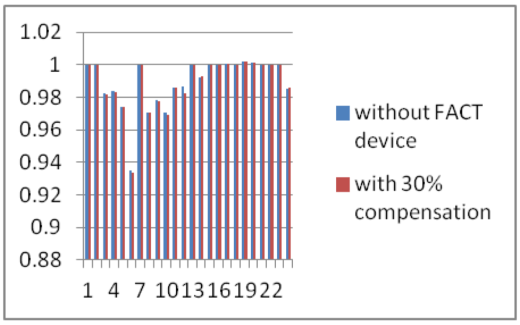
The list of power flows are

Line	From bus	To bus	Without FACT device	With TCPAR	
				20% compensation	30% compensation
1	1	2	137.67	137.2	137.4
2	1	3	25.53	28	28.2
3	1	5	113.81	112.5	112.8
4	2	4	52.62	52.2	52.4
5	2	6	24.87	24.8	24.9
6	3	9	49.86	44.8	44.8
7	3	24	144.68	137.2	137
8	4	9	41.69	40.8	41
9	5	10	50.9	49.7	49.9
10	6	10	111	114.4	114.4
11	7	8	100	100	100
12	8	9	104.7	109.8	109.8
13	8	10	87.92	92.2	92.2
14	9	11	67.73	60.3	60.2
15	9	12	62.17	74.5	74.4
16	10	11	100.74	92	91.9
17	10	12	95.27	106	105.9
18	11	13	35.9	37	36.9
19	11	14	132.94	115.4	115.3
20	12	13	45.64	11.7	11.6
21	12	23	112.99	168.9	168.8
22	13	23	101.81	68.9	68.8
23	14	16	163.87	146.1	146
24	15	16	50.05	52.4	52.3
25	15	21	26.68	29.4	29.3
26	15	21	26.68	29.4	29.3
27	15	24	146.58	138.9	138.7
28	16	17	161.88	167.1	167
29	16	19	36.71	62.2	62.3
30	17	18	133.59	138.1	138.1
31	17	22	29.14	29.9	29.8
32	18	21	41.96	44.2	44.2
33	18	21	41.96	44.2	44.2
34	19	20	13.33	26.1	26.1
35	19	20	13.33	26.1	26.1
36	20	23	8.32	21	21
37	20	23	8.32	21	21
38	21	22	0.76	0	0

Power flow comparison with and without FACT device as



Comparison of voltage profiles with and without TCPAR as



Voltage profile comparison with and without FACT devices for IEEE-24 bus system

VI. Conclusion

The challenge for engineers is to produce and provide an electrical energy to consumers in a safe, economical and environmentally friendly manner under various constraints. Congestion management is one of the challenging tasks in deregulated power system environment. In deregulated environment, the location of FACTS devices and their control can significantly affect the operation of the system. In this paper congestion management is done by using FACTS devices i.e. TCSC and TCPAR. The method of mitigation of total system var power loss is used to allocate the TCSC and TCPAR in optimal location. This optimal location gives the better results from the FACTS devices in order to alleviate the congestion in the transmission system. By placing TCSC and TCPAR in the system the congestion cost is reduced to zero and power flow and voltage profiles limits also increased. The sensitivity approach is proposed in this work will give the solution for determining optimal location of FACTS devices in a deregulated power system to relieve congestion on system. This method was successfully tested on modified IEEE 14 and IEEE 24 bus system.

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