ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526

INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH IN ELECTRICAL, ELECTRONICS, INSTRUMENTATION AND CONTROL ENGINEERING
Vol. 3, Issue 11, November 2015

Enhancement of Transfer Capability in a deregulated environment using TCSC under contingency

M Venkateswara Rao[1], Sirigiri Sivanagaraju[2]

Associate Professor in PE, GMR Institute of Technology, Rajam, Srikakulam, Andhra Pradesh, India[1]

Professor in EEE, UCEK, Kakinada, JNTUK, Kakinada, Andhra Pradesh, India[2]

Abstract: Transfer capability is a key aspect to be taken care by both the power system operators and consumers. Since the load on the power system network increases day by day, the effective utilization of power transmission network is a major criterion to be concentrated in power system network operations. In this paper there are two aspects considered to understand the security of network. Initially the performance of the network is analyzed under contingency condition and later the system performance is also analyzed with the usage of the series FACTS device i.e. TCSC. The methodology is tested in IEEE-30 bus test system.

Keywords*:* ATC; Bi-lateral Transaction; ACPTDF; contingency analysis; Power Injection model of TCSC.

I.INTRODUCTION

Throughout the world the electric industry aims at creating the competitive market for effective utilization of a power system networks. Sufficient power flow should be guaranteed for trading and maintain economical issues in a power networks for both power generation companies and consumers. These aspects have motivated to calculate the excess available power in transmission networks to evaluate the Available Transfer Capability (ATC).System operators are mainly responsible in determination of ATC, for both bi-lateral and multi lateral transactions. Many authors have proposed the methodology to identify the ATC considering static limits such as line thermal limit, bus voltage limits and steady state stability limits constraints.

Based on DC load flow optimization method has been presented in [1].Linear sensitivity factor methods are proposed in [2]. Practically in a open access electricity market , when the generation schedules and load s are continuously varying, the system is subjected to either small or large disturbances. Since the system is dynamic in nature, the ATC calculated with the dynamic stability limits is proposed in [3]. Ref. [4], proposes a model to illustrate dynamic constraints ATC, using equilibrium equations. in Ref. [5], A hybrid energy function method has been proposed to enhance the dynamic ATC through optimal placement of FACTS controllers. Introduction of FACTS devices into transmission network results in improving the transmission capability which will be an effective and promising alternative to conventional methods of ATC enhancement. These devices will provide new control possibilities , both in steady state power flow control and dynamic stability control [6]. There are many optimization methods have been proposed to calculate the ATC, based on Security Constrained Optimal Power Flow (SCOPF)[7-8], Continuous Power Flow method [9-10], Repeated Power Flow methods [11] using FACTS devices.

II. OPERATING PRINCIPLE OF ATC

TCSC is one of the series compensator; it can capable to control power flow in line, damping power oscillations. Basic simple TCSC model is shown in Fig.1.TCSC is formed by connecting the capacitor in series with the transmission line and thyristor-controlled reactor (TCR) in parallel with capacitor. TCSC is simple construction and less cost compared to other series FACTS devices. Power transfer in the lines can be controlled by controlling the net series impedance of the line.

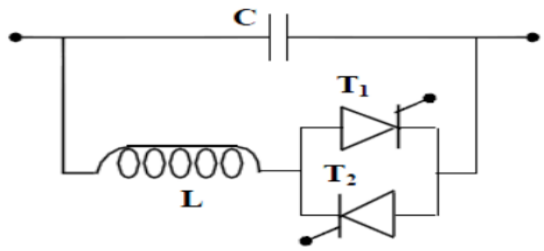

Fig. 1 Model of TCSC

A simple transmission system represented π equivalent parameters connected between bus-k and bus-m. The real and reactive power flows from bus-k to bus-m can be written as

$$P_{km} = V_k^2 G_{km} - V_k V_m \left[G_{km} Cos(\delta_{km}) + B_{km} Sin(\delta_{km})\right] \quad (1)$$

$$Q_{km} = -V_k^2 (B_{km} + B_{sh}) - V_k V_m \left[G_{km} Sin(\delta_{km}) - B_{km} Cos(\delta_{km})\right] \quad (2)$$

Where $\delta_{km} = \delta_k - \delta_m = -\delta_{mk}$

The real and reactive power flows from bus-m to bus-k is

$$P_{mk} = V_m^2 G_{km} - V_k V_m \left[G_{km} Cos(\delta_{km}) - B_{km} Sin(\delta_{km})\right] \quad (3)$$

$$Q_{mk} = -V_m^2 (B_{km} + B_{sh}) + V_k V_m \left[G_{km} Sin(\delta_{km}) + B_{km} Cos(\delta_{km})\right] \quad (4)$$

A. Power Injection Model of TCSC

Fig.2 shows a π model of transmission line with TCSC connected between bus-k and bus-m. Under the steady state condition, the TCSC can be represented as a static reactance $-jX_C$. In the power flow equations the

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ISSN (Print) 2321 – 5526
INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH IN ELECTRICAL, ELECTRONICS, INSTRUMENTATION AND CONTROL ENGINEERING
Vol. 3, Issue 11, November 2015

controllable reactance X_C is directly used as the control variable.

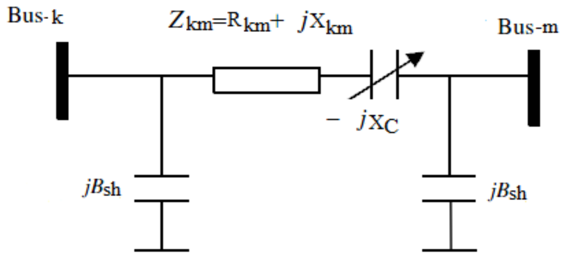

Fig.2 Transmission line with TCSC

The line data will be modified by placing TCSC in series with line. A new line reactance is given as follows

$$X_{km\,new} = X_{km} - X_C \tag{5}$$

Therefore new line admittance between buses k and m can be derived as follows

$$Y'_{km} = \frac{1}{Z'_{km}} = \frac{1}{R_{km} + j(X_{km} - X_C)} \tag{6}$$

$$Y'_{km} = G'_{km} + jB'_{km} = \frac{R_{km} - j(X_{km} - X_C)}{R_{km}^2 + (X_{km} - X_C)^2} \tag{7}$$

(8)

$$B'_{km} = -\frac{(X_{km} - X_C)}{R_{km}^2 + (X_{km} - X_C)^2} \tag{9}$$

The modified active and reactive power flows from bus-k to bus-m, and from bus-m to bus-k of a line having series impedance and a series reactance are

$$P_{km}^{TCSC} = V_k^2 G'_{km} - V_k V_m \left(G'_{km} Cos(\delta_{km}) + B'_{km} Sin(\delta_{km})\right) \tag{10}$$

$$Q_{km}^{TCSC} = -V_k^2 (B'_{km} + B_{sh}) - V_k V_m \left(G'_{km} Sin(\delta_{km}) - B'_{km} Cos(\delta_{km})\right) \tag{11}$$

$$P_{mk}^{TCSC} = V_m^2 G'_{km} - V_k V_m \left(G'_{km} Cos(\delta_{km}) - B'_{km} Sin(\delta_{km})\right) \tag{12}$$

$$Q_{mk}^{TCSC} = -V_m^2 (B'_{km} + B_{sh}) + V_k V_m \left(G'_{km} Sin(\delta_{km}) + B'_{km} Cos(\delta_{km})\right) \tag{13}$$

The power loss in the line with TCSC can be written as

$$P_{Loss} = P_{km}^{TCSC} + P_{mk}^{TCSC} = G'_{km}(V_k^2 + V_m^2) - 2V_k V_m G'_{km} Cos(\delta_{km}) \tag{14}$$

$$Q_{Loss} = Q_{km}^{TCSC} + Q_{mk}^{TCSC} = -(V_k^2 + V_m^2)(B'_{km} + B_{sh}) + 2V_k V_m B'_{km} Cos(\delta_{km}) \tag{15}$$

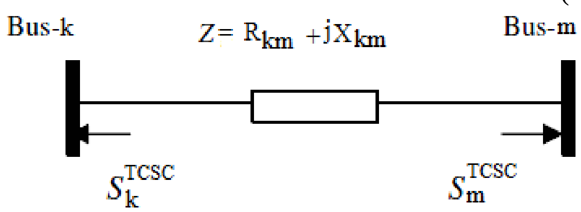

Fig.3 Power injection model of TCSC

Due to TCSC, the change in line flow can be represented as a line without TCSC plus with power injected at the sending and receiving ends of the line with device as shown in Fig. 3. The active and reactive power injections at bus-k and bus-m can be written as

$$\begin{aligned} P_k^{TCSC} &= P_{km} - P_{km}^{TCSC} \\ &= V_k^2 \Delta G_{km} - V_k V_m [\Delta G_{km} Cos(\delta_{km}) + \Delta B_{km} Sin(\delta_{km})] \end{aligned} \tag{16}$$

$$\begin{aligned} P_m^{TCSC} &= P_{mk} - P_{mk}^{TCSC} \\ &= V_m^2 \Delta G_{km} - V_k V_m [\Delta G_{km} Cos(\delta_{km}) - \Delta B_{km} Sin(\delta_{km})] \end{aligned} \tag{17}$$

$$\begin{aligned} Q_k^{TCSC} &= Q_{km} - Q_{km}^{TCSC} \\ &= -V_k^2 \Delta B_{km} - V_k V_m [\Delta G_{km} Sin(\delta_{km}) - \Delta B_{km} Cos(\delta_{km})] \end{aligned} \tag{18}$$

$$\begin{aligned} Q_m^{TCSC} &= Q_{mk} - Q_{mk}^{TCSC} \\ &= -V_m^2 \Delta B_{km} + V_k V_m [\Delta G_{km} Sin(\delta_{km}) + \Delta B_{km} Cos(\delta_{km})] \end{aligned} \tag{19}$$

Where

$$\Delta G_{km} = \frac{X_C R_{km} (X_C - 2X_{km})}{(R_{km}^2 + X_{km}^2)(R_{km}^2 + (X_{km} - X_C)^2)} \tag{20}$$

$$\Delta B_{km} = \frac{-X_C (R_{km}^2 - X_{km}^2 + X_C X_{km})}{(R_{km}^2 + X_{km}^2)(R_{km}^2 + (X_{km} - X_C)^2)} \tag{21}$$

TCSC device is modelled with power injection model so far by using the TCSC control variable. It is possible to calculate the complex power injected S_k^{TCSC} and S_m^{TCSC} at bus-k and bus-m respectively.

$$S_k^{TCSC} = P_k^{TCSC} + jQ_k^{TCSC} \tag{22}$$

$$S_m^{TCSC} = P_m^{TCSC} + jQ_m^{TCSC} \tag{23}$$

Then new power flow equations can be expressed by the following relationship

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} H_{new} & M_{new} \\ N_{new} & L_{new} \end{bmatrix} \cdot \begin{bmatrix} \Delta\delta \\ \frac{\Delta V}{V} \end{bmatrix} \tag{24}$$

Where new mismatch vectors are

$$\Delta P_i = P_k^{spec} + P_k^{TCSC} - P_k^{calc} \tag{25}$$

$$\Delta Q_i = Q_k^{spec} + Q_k^{TCSC} - Q_k^{calc} \tag{26}$$

P_k^{spec} and Q_k^{spec} are the classical specified real and reactive powers, P_k^{TCSC} and Q_k^{TCSC} are the power injection associated to TCSC devices, P_k^{calc} and Q_k^{calc} are computed using the power flow equations. Now modified Jacobian matrix due to power injections of TCSC

DOI 10.17148/IJIREEICE.2015.31117

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ISSN (Print) 2321 – 5526
INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH IN ELECTRICAL, ELECTRONICS, INSTRUMENTATION AND CONTROL ENGINEERING
Vol. 3, Issue 11, November 2015

$$H_{new} = H + \frac{\partial P^{TCSC}}{\partial \delta} \;;\; M_{new} = M + \frac{\partial P^{TCSC}}{\partial V} V \quad (27)$$

$$N_{new} = N + \frac{\partial Q^{TCSC}}{\partial \delta} \;;\; L_{new} = L + \frac{\partial Q^{TCSC}}{\partial V} V \quad (28)$$

H, M, N and L are the classic sub-Jacobians.

III. ACPTDF DETERMINATION

From the power transfer point of view, a transaction is a specific amount of power that is injected into the system at one bus by a generator and drawn at another bus by a load. The coefficient of linear relationship between the amount of a transaction and flow on a line is represented by PTDF. It is also called sensitivity because it relates the amount of one change - transaction amount - to another change - line power flow.

PTDF is the fraction of amount of a transaction from one bus to another that flows over a transmission line $PTDF_{lm,ji}$ is the fraction of a transaction from bus i to bus j that flows over a transmission line connecting buses l and m.

$$PTDF_{lm,ji} = \frac{\Delta P_{lm}}{P_{ji}}$$

Available Transfer Capability (ATC) is determined by recognizing the new flow on the line from node I to node m, due to a transaction from node I to node j. The new flow on the line is the sum of original flow P_{lm}^{0}

$$P_{lm} = P_{lm}^{0} + PTDF_{lm,ij} P_{ij}$$

Where, P_{lm}^{0} is the base case flow on the line and P_{ji} is the magnitude of proposed transfer. If the limit on line Im, the maximum power that can be transferred without overloading line Im, is $P_{lm}^{\max}$, then,

$$P_{ij,lm}^{\max} = \frac{P_{lm}^{\max} - P_{lm}^{0}}{PTDF_{lm,ij}}$$

$P_{ij,lm}^{\max}$ is the maximum allowable transaction from node I to node j constrained by the line from node I to node m. ATC is the minimum of the maximum allowable transactions over all lines. Using the above equation, any proposed transaction for a specific hour may be checked by calculating ATC. If it is greater than the amount of the proposed transaction, the transaction is allowed. If not, the transaction must be rejected or limited to the ATC.

$$ATC_{ij} = \min\left(P_{ij,lm}^{\max}\right)$$

Using the above equation, any proposed transaction for a specific hour may be checked by calculating ATC. If it is greater than the amount of the proposed transaction, the transaction is allowed. If not, the transaction must be rejected or limited to the ATC. The detailed analysis regarding the calculations of ATC values for any power system network has been given in [12].

If a change in the transmission line quantity is ΔP_{ij} for a transaction of P_{mn} among the seller and buyer bus with FACTS, the ACPTDF can be calculated as

$$ACPTDF_{mn,FACTS}^{ij} = \frac{\Delta P_{ij}^{\text{FACTS}}}{P_{mn}}$$

For PTDF calculations with FACTS, the power flow sensitivity and N-R load flow Jacobian matrix can be calculated. The change in power flow at any bus i can be formulated in terms of Jacobian as:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{1,\text{FACTS}} & J_{2,\text{FACTS}} \\ J_{3,\text{FACTS}} & J_{4,\text{FACTS}} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix}$$

Based on these equations the change in the angle and voltage magnitudes can be determined. Based on the ACPTDF values, the best possible location of FACTS has been identified to evaluate the ATC values for possible transactions. To identify the sensitive generator in contingency analysis, based on the literature, a methodology named as voltage sensitivity indexes are calculated to identify the most critical generator. Based on this approach, the generator number eight is identified as a most critical generator. Hence the evaluation of ATC is being done based on this methodology only.

IV. RESULT AND DISCUSSION

The proposed ATC evaluation procedure is implemented on IEEE 30 Bus System by using TCSC at suitable locations. This test system is having six generators and forty one transmission lines. However out of thirty buses, the loads are connected to twenty one buses only. Since out of these one bus is taken as a slack bus (bus - 1), therefore the possible bi-lateral transactions with generator at bus -2 under contingency are listed in Table 1 and also variation of ATC values for possible bi-lateral transactions with generator at bus-2 is shown in Fig.5.It is observed that, when the system is under contingency, the ATC values are marginally reduced in all the cases in both the conditions(i.e with and without device).

Similarly ATC values for possible bi-lateral transactions with generator at bus-5, 8, 11&13 are shown in Table.2, 3, 4&5 respectively. The corresponding variations of ATC with FACTS devices are represented in Fig.5, 6, 7 & 8. Hence it is evident that, the series FACTS devices will be useful in enhancing the power flow in any power transmission networks.

Table.1. ATC evaluation for possible bi-lateral transactions with generator at bus-2

S. No.	Transaction Details		ATC			
	Generator bus number	Load bus number	Without TCSC	Without TCSC under contingency	With TCSC	With TCSC under contingency
1	2	3	121.0226	55.40677	121.5042	55.53212
2		4	104.2924	70.36753	104.3477	70.51053
3		5	123.0127	122.4224	123.8774	122.6395

4		7	45.53516	41.99607	45.55606	42.08436
5		8	26.79385	21.69433	26.87944	21.73919
6		10	25.62739	19.10099	25.70357	19.14101
7		12	71.27687	65.30579	71.87067	65.44853
8		14	22.55846	21.34121	22.70769	21.38243
9		15	20.63313	18.62103	20.77723	18.66213
10		16	37.82207	35.51697	37.98318	35.59206
11		17	22.73442	21.03851	23.94177	21.08329
12		18	10.71314	10.30021	10.98517	10.32124
13		19	9.335798	8.882043	9.422176	8.900475
14		20	11.89237	11.16423	11.99032	11.18647
15		21	12.72176	10.79996	12.98677	10.82214
16		23	10.39978	9.944401	10.52607	9.96524
17		24	11.53429	10.49905	11.81577	10.52101
18		26	7.459279	7.177555	7.498455	7.192638
19		29	8.924289	8.393205	9.130661	8.410861
20		30	9.900268	9.361762	10.11473	9.381462

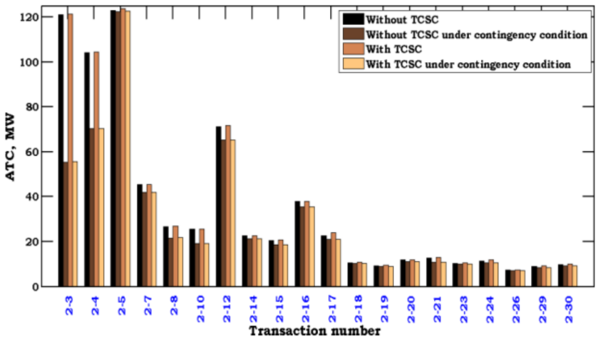

Fig. 4.Variation of ATC values for possible bi-lateral transactions with generator at bus-2

Table.2. ATC evaluation for possible bi-lateral transactions with generator at bus-5

S. No.	Transaction Details		ATC			
	Generator bus number	Load bus number	Without TCSC	Without TCSC under contingency	With TCSC	With TCSC under contingency
1	5	2	199.3174	198.1584	199.7518	198.5745
2		3	144.7646	59.38463	144.8308	59.50934
3		4	147.0735	83.39195	146.8358	83.56707
4		7	45.45157	42.63063	45.55104	42.72015
5		8	27.07453	22.27865	26.78608	22.32544
6		10	26.67073	20.00338	26.48097	20.04539
7		12	73.14996	69.79973	72.70225	69.94631
8		14	22.67424	21.53755	22.29668	21.58278
9		15	21.15746	19.18763	21.09544	19.22792
10		16	38.60395	36.37195	38.37262	36.44833

11		17	23.28306	21.61264	23.11379	21.65803
12		18	10.79716	10.40389	10.76057	10.42574
13		19	9.410203	8.976521	9.378295	8.995372
14		20	12.01336	11.3139	11.95158	11.33766
15		21	12.97692	11.08264	12.92191	11.10591
16		23	19.48321	10.04692	19.42413	10.06802
17		24	11.62149	10.62249	11.56807	10.6448
18		26	7.476314	7.205254	7.490962	7.220385
19		29	8.951354	8.436807	8.820036	8.454524
20		30	9.925533	9.402896	9.912321	9.422642

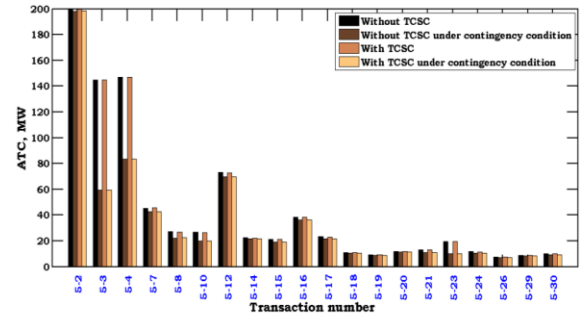

Fig. 5.Variation of ATC values for possible bi-lateral transactions with generator at bus-2

Table 3. ATC evaluation for possible bi-lateral transactions with generator at bus-2

S. No.	Transaction Details		ATC			
	Generator bus number	Load bus number	Without TCSC	Without TCSC under contingency	With TCSC	With TCSC under contingency
1	8	2	45.37419	36.70989	45.75345	36.78698
2		3	49.79933	48.33312	49.83746	48.43462
3		4	51.45711	51.39923	51.48502	51.40717
4		5	45.84946	37.69864	45.86237	37.77781
5		7	48.80121	45.71734	48.98823	45.81335
6		10	28.23243	27.76628	28.87342	27.82459
7		12	52.50883	45.19769	52.60344	45.29261
8		14	22.86497	21.0129	22.95833	21.05703
9		15	21.87428	20.70111	21.95778	20.74458
10		16	39.54883	38.4762	39.73541	38.557
11		17	23.95097	22.93048	23.98483	22.97863
12		18	10.90171	9.11859	10.94358	9.137739
13		19	9.504393	9.215393	9.577355	9.234745
14		20	12.16731	12.01337	12.66233	12.0386
15		21	13.33502	13.31537	13.86728	13.34333
16		23	10.61538	10.59225	10.91536	10.61449
17		24	11.80904	11.07458	11.98738	11.09784
18		26	7.512583	7.510282	7.913757	7.526054
19		29	9.014172	8.955205	9.815754	8.974011
20		30	9.984077	9.886976	9.997743	9.907739

ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526

IJIREEICE

INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH IN ELECTRICAL, ELECTRONICS, INSTRUMENTATION AND CONTROL ENGINEERING
Vol. 3, Issue 11, November 2015

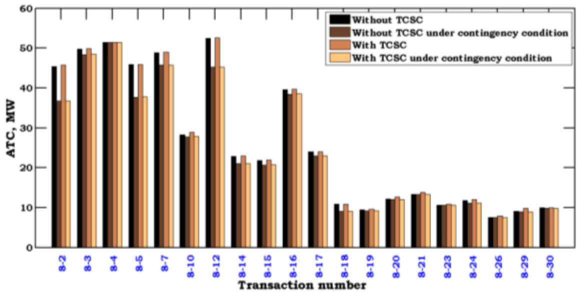

Fig. 6.Variation of ATC values for possible bi-lateral transactions with generator at bus-2

Table 4. ATC evaluation for possible bi-lateral transactions with generator at bus-2

S. No.	Transaction Details		ATC			
	Generator bus number	Load bus number	Without TCSC	Without TCSC under contingency	With TCSC	With TCSC under contingency
1		3	42.93515	29.70067	42.97742	29.76304
2		4	42.96768	42.9552	42.99395	43.04541
3		5	42.97808	42.16956	42.79949	42.25812
4		7	42.93976	32.15258	42.99134	32.2201
5		8	42.98265	42.13227	42.99453	42.22075
6		10	30.30812	30.24181	30.42632	30.30532
7		12	41.25571	41.20617	41.40862	41.2927
8		14	35.10306	32.1804	34.89735	32.24798
9		15	23.50712	23.15872	23.76820	23.20735
10		16	29.41206	29.11923	29.73556	29.18038
11	11	17	42.99744	42.99644	43.03679	43.02673
12		18	32.41835	31.71369	32.44532	31.78029
13		19	11.84646	11.79448	11.87342	11.81925
14		20	10.38229	10.30135	10.39932	10.32298
15		21	13.64426	13.50261	13.65232	13.53097
16		23	16.87937	16.22781	16.97672	16.26189
17		24	11.08327	10.98902	11.09732	11.0121
18		26	11.81592	11.51184	11.74804	11.53601
19		29	7.500342	7.386636	7.551783	7.402148
20		30	8.925488	8.675149	8.931924	8.693367

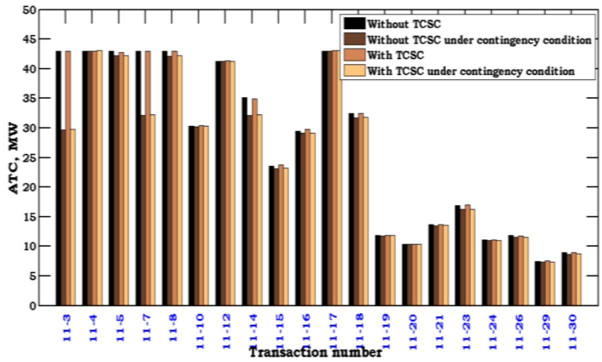

Fig. 7.Variation of ATC values for possible bi-lateral transactions with generator at bus-2

Table 5. ATC evaluation for possible bi-lateral transactions with generator at bus-2

S. No.	Transaction Details		ATC			
	Generator bus number	Load bus number	Without TCSC	Without TCSC under contingency	With TCSC	With TCSC under contingency
1		3	37.05011	37.01009	37.14593	37.08781
2		4	37.07172	37.05822	37.14359	37.13604
3		5	37.07966	37.07468	37.17554	37.15254
4		7	37.05749	37.02129	37.14432	37.09903
5		8	37.08627	37.08494	37.17617	37.16282
6		10	30.84099	30.16772	30.91542	30.23107
7		12	20.79596	19.00624	20.84713	19.04615
8		14	37.01009	36.01187	37.09881	36.08749
9		15	25.45671	25.20571	25.51867	25.25864
10	13	16	15.90949	15.60288	15.94834	15.63565
11		17	29.01607	28.00472	29.08428	28.06353
12		18	17.08249	16.75173	17.12606	16.78691
13		19	10.08673	9.966713	10.11409	9.987643
14		20	8.832218	8.686702	8.852775	8.704944
15		21	11.08711	10.85734	11.11579	10.88014
16		23	11.40628	10.1696	11.43217	10.19096
17		24	9.783025	9.625115	9.805694	9.645328
18		26	11.41634	10.01641	11.44288	10.03744
19		29	7.369722	7.219257	7.386797	7.234417
20		30	8.760177	8.451512	8.780478	8.46926

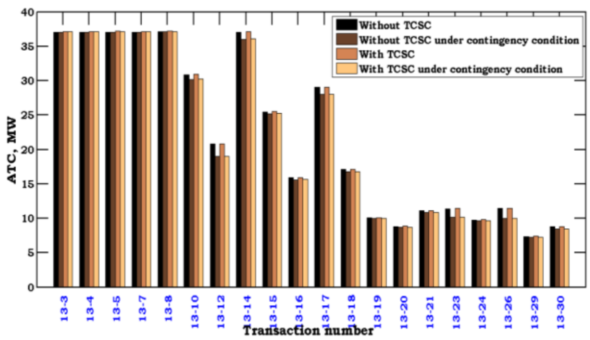

Fig. 8.Variation of ATC values for possible bi-lateral transactions with generator at bus-2

V.CONCLUSION

The paper has developed a methodology to calculate the ATC values for all possible bi-lateral transactions. The performance of the network is analyzed using a series FACTS device i.e TCSC. The ATC values are also presented for both normal and contingency conditions. It is evident that, the transfer capability of the power system network is enhanced with the series FACTS device and thereby improving transmission services of the deregulated power system market. In this paper, the proposed technique tested on IEEE 30 bus system. From the above results, it is clear that the proposed method improves the available transfer capability.

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ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526

INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH IN ELECTRICAL, ELECTRONICS, INSTRUMENTATION AND CONTROL ENGINEERING
Vol. 3, Issue 11, November 2015

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 DOI 10.17148/IJIREEICE.2015.31117