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Assessment of ATC with Shunt FACTS Devices

Ashwani Kumar, Jitender Kumar

***Abstract*—**In this paper, an optimal power flow based approach has been applied for multi-transactions deregulated environment for ATC determination with SVC and STATCOM. The main contribution of the paper is (i) OPF based approach for evaluation of ATC with multi-transactions, (ii) ATC enhancement with FACTS devices viz. SVC and STATCOM for intact and line contingency cases, (iii) Impact of ZIP load on ATC determination and comparison of ATC obtained with SVC and STATCOM. The results have been determined for intact and line contingency cases taking simultaneous as well as single transaction cases for IEEE 24 bus RTS.

***Keywords*—**Available transfer capability, FACTS devices, line contingency, multi-transactions, ZIP load model.

I. Introduction

AVAILABLE transfer capability is one of the key components to access the transmission network capability for secure and reliable operation of a system [1], [2]. ATC has been determined utilizing the DC and AC sensitivity based approaches determining PTDFs under intact and line outage contingency cases [3]-[13]. The method is fast as sensitivity factors for DC method needs no repeated computation and in case of AC method, no assumptions are involved and N-R Jacobian has been utilized with different cases of transactions and methods for PTDFs calculations.

Optimal power based approaches have also been utilized by many authors for ATC determination as these approaches can give better solution to ATC determination subject to the fulfillment of constraints in the network [14]-[16]. In this paper, non-linear optimal power flow problem has been solved for ATC determination for different bilateral and simultaneous transactions. ATC has also been determined with FACTS devices considering all types of series, shunt and series-shunt FACTS controllers like TCSC, SVC, STATCOM, SSSC and UPFC [14]-[21]. ATC can be enhanced with these FACTS controllers. In addition to the FACTS devices, another power flow control device called as Sen Transformer (ST) has also been modeled in [21] for ATC enhancement.

Many authors have determined ATC with optimal power flow approach considering only constant PQ model of loads. However, impact of the generalized load model remains un-addressed to determine ATC. The constant impedance, constant current and constant power (ZIP) model has also been incorporated in ATC determination without and with SVC and STATCOM devices. The comparison of shunt FACTS devices viz. SVC and STATCOM has been presented for both the bilateral and multilateral transactions. The power flow models of FACTS devices has been incorporated in an OPF model to find their impact on ATC enhancement. The model of these devices has been well explained in [22]. The problem formulated is solved using an optimal power flow technique based on the non linear programming utilizing CONOPT solver of GAMS and MATLAB interfacing [23]. Modeling of ZIP load has been also considered with and without FACTS devices for different transactions. The results have been obtained for IEEE 24 bus RTS for different transactions [24].

Ashwani Kumar is with the national Institute of Technology, Kurukshetra, India (phone: +911744233389; fax: +911744238050; e-mail: ashwaks@ gmail.com).

Jitender Kumar is with the Department of Electrical Engineering at IIT Roorkee and is pursuing his PhD at IIT Roorkee, India (e-mail: jeetusingh61@gmail.com).

II. Formulation of ATC Calculation

A. Review Stage

ATC has been determined without and with FACTS devices for different transactions. For bilateral transactions, the parameter λ has been maximized corresponding to the seller and buyer buses subject to equality and inequality constraints. For simultaneous /multi-transactions, the two parameters corresponding to seller and buyer buses have been added and maximized subject to equality and inequality constraints. A general OPF based approach for ATC determination can be formulated as: An OPF based approach can be formulated as:

The general form of the problem formulation can be represented as.

$$\text{Min } F(x,u,p,\xi_{FACTS}) \tag{1}$$

Subject to equality and inequality constraints defined as:

$$h(x,u,p,\xi_{FACTS}) = 0 \tag{2}$$

$$g(x,u,p,\xi_{FACTS}) \le 0 \tag{3}$$

where,

x is state vector of variables V, δ; u are the control parameters, P_{gi}, Q_{gi};

p are the fixed parameters P_{di}, Q_{di}, ξ_{FACTS} are control parameters for all types of FACTS devices.

Objective function can be defined for single transaction case as:

Max λ

Subject to constraints:

(i) Equality Constraints: The equality constraints are the power injections at all the buses and can be represented as:

Real power injection equations at any bus *i* from load flow analysis given as:

$$P_i - \sum_{j=1}^{n} V_i V_j [G_{ij} \cos(\delta_{ij}) + B_{ij} \sin(\delta_{ij})] = 0 \quad (4)$$

Reactive power injection equations at any bus *i* from load flow analysis given as

$$Q_i - \sum_{j=1}^{n} V_i V_j \left[G_{ij} \sin(\delta_{ij}) - B_{ij} \cos(\delta_{ij})\right] = 0 \quad (5)$$

where n is the total no of buses and P_i and Q_i are the injected real and reactive power at any bus *i*.

$$P_i = P_{Gi} - P_{Di} \quad (6)$$

$$Q_i = Q_{Gi} - Q_{Di} \quad (7)$$

(ii) Inequality constraints: The inequality constraints can be represented as:

Voltage limit:

$$V_{i\min} < V_i < V_{i\max} \quad (8)$$

$$V_{j\min} < V_j < V_{j\max} \quad (9)$$

Angle limit

$$\delta_{i\min} < \delta_i < \delta_{i\max} \quad (10)$$

$$\delta_{j\min} < \delta_j < \delta_{j\max} \quad (11)$$

Real and reactive power generation of generators can be represented as:

$$P_{Gi\min} < P_{Gi} < P_{Gi\max} \quad (12)$$

$$Q_{Gi\min} < Q_{Gi} < Q_{Gi\max} \quad (13)$$

Line flow constraints:

$$P_{ij\min} < P_{ij} < P_{ij\max} \quad (14)$$

$$Q_{ij\min} < Q_{ij} < Q_{ij\max} \quad (15)$$

where

P_{Gi} real power generation at any bus *i*.

Q_{Gi} reactive power generation at any bus *i*.

P_{Di} and Q_{Di} are the real and reactive load at any bus *i*.

V_i and V_j are the voltage at buses *i* and *j*.

$\delta_i and \delta_j$ are voltage angles at buses *i* and *j*.

$P_{Gi\ max}$ and $P_{Gi\ min}$, $Q_{Gi\ max}$ and $Q_{Gi\ min}$ are the maximum and minimum limits of real and reactive power generation at any bus *i*.

$P_{ij\ max}$ and $P_{ij\ min}$, $Q_{ij\ max}$ and $Q_{ij\ min}$ are the maximum and minimum limits of real and reactive power flow from bus *i* to bus *j*.

For bilateral transactions, the parameter can be represented as:

For calculating ATC, the change generation and load at a seller bus and buyer bus in (5.30) can be obtained using generation and demand at corresponding buses as:

$$P_{Gm} = \lambda P_{Gm}^{o} \quad (16)$$

$$P_{Dn} = \lambda P_{Dn}^{o} \quad (17)$$

where *m* is the seller bus and *n* is the buyer bus and $P_{Gm} and P_{Dn}$ are real power generation and load corresponding to the bus m and n.

ATC can be calculated as:

$$ATC = \lambda P_{Dn} \quad (18)$$

For multilateral transaction case, if sb=m1, m2, .. ,mm are the seller buses and bb= n1, n2..nn are the buyer buses, then the corresponding entries for seller buses and buyer buses can be modified in the power injection equation as:

$$P_{Gm1} = \lambda_1 P_{Gm1}^{o};\ P_{Gm2} = \lambda_2 P_{Gm2}^{o} \ldots\ldots\ldots\ldots = \lambda_n P_{Gmm}^{0} \quad (19)$$

$$P_{Dn1} = \lambda_1 P_{Dn1}^{o}; P_{Dn2} = \lambda_2 P_{Dn2}^{0} \ldots\ldots\ldots\ldots\ldots = \lambda_n P_{Dnn}^{0} \quad (20)$$

For simultaneous transactions, ATC can be obtained as:

$$\text{Max } \lambda_T = \sum_{sb=m1}^{sb=mm} \lambda_{sb} = \sum_{bb=n1}^{bb=nn} \lambda_{bb} \quad (21)$$

The non-linear optimization problem has been solved using GAMS and MATLAB interfacing [23]. The CONOPT solver of GAMS has been called in MATLAB environment to obtain the optimized value of ATC supplying all variables to GAMS computed in MATLAB environment.

III. Modeling of ZIP Load

A static load model expresses the characteristic of the load at any instant of times as algebraic functions of the bus voltage magnitude and the frequency at that instant. The voltage dependency of the load characteristics has been represented by exponential model as:

$$P_d = P_d^0 (\overline{V})^a \quad (22)$$

$$Q_d = Q_d^0 (\overline{V})^b \quad (23)$$

where, $\overline{V} = \frac{V}{V^0}$ and P_d and Q_d are the active and reactive component of the load when the bus voltage magnitude is V. The subscript 0 identifies the values of the respective variables at the initial operating condition. For the composite system loads, the exponent a lies between 0.5 and 1.8 and exponent b lies in between 1.5 to 6. ZIP load depends upon the values of a and b. So, ZIP load is the combination of constant impedance, constant current and constant active power load. For constant impedance, value of a is 2. For constant current, value of a is 1 and for constant power, a is 0. So, ZIP load can be represented by these equations as given below:

$$P_d = P_{d0}[p1\overline{V}^2 + p2\overline{V} + p3] \tag{24}$$

$$Q_d = Q_{d0}[q1\overline{V}^2 + q2\overline{V} + q3] \tag{25}$$

where p1 to p2 and q1 to q2 are load coefficients of the model. $p1 + p2 + p3 = 1$ and $q1 + q2 + q3 = 1$

The power injection equations taken as equality constraints can be modified at a particular load bus using (24) and (25) in an OPF model for the calculation of ATC. For incorporation of all FACTS devices, an OPF model can be modified changing power flow equations with the equations for all FACTS devices as discussed in [22].

IV. Results and Discussions

In this chapter, ATC has been determined using an OPF approach. ATC has been determined without and with all FACTS devices. The mathematical equations governing power flow equations for FACTS devices Viz. SVC, STATCOM, TCSC, SSSC, and UPFC have already been presented in the previous chapter. Other generalized FACTS devices power flow model has been described in section 5.2. The power flow equations for IPFC, GUPFC and ST are can be added in OPF model for ATC determination. The results have been determined and are presented in tabular form and bar charts form.

ATC has been obtained for different transactions taken as single transactions and simultaneous/multi-transactions. These transactions have been categorized as:

T1: transaction between seller bus 23 to buyer bus 15

T2: transaction between seller bus 10 to buyer bus 3

T3: simultaneous transaction between seller buses 23, 10 to buyer bus 15, 3

ZIP load is considered at bus 5. Different combinations of load coefficients are taken for voltage dependent ZIP load for ATC determination.

For ZIP load model, the coefficients are: *p1=q1*; *p2=q2* and *p3=q3*.

A. ATC without and with ZIP Load

ATCs obtained without and with line outages for different transactions are given in Table I and also shown in Figs. 1 and 2. It is observed that ATC is found higher for transaction T1 compare to all other transactions. ATCs with line contingency case are observed lower as compare to those of without line contingency case.

TABLE I
ATC (p.u) without and with Line Contingency Case

	ATC(p.u)		
	T1	T2	T3
No line outage	7.8869	3.0333	4.0323
With SVC at bus 6	8.6804	3.2832	4.1508
STATCOM at bus 6	8.8764	3.3403	4.1745
Outaged line without SVC/STATCOM			
9-12	4.9809	2.2142	3.5066
16-19	6.4931	3.0239	3.1590
19-20	7.0909	2.9350	3.6460
20-23	7.2033	2.9342	3.6829

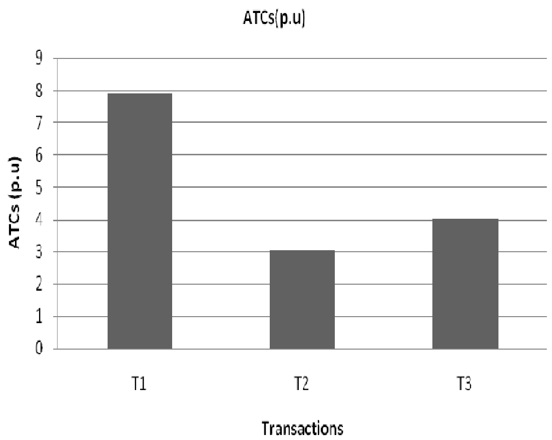

Fig. 1 ATCs (p.u) for different transaction

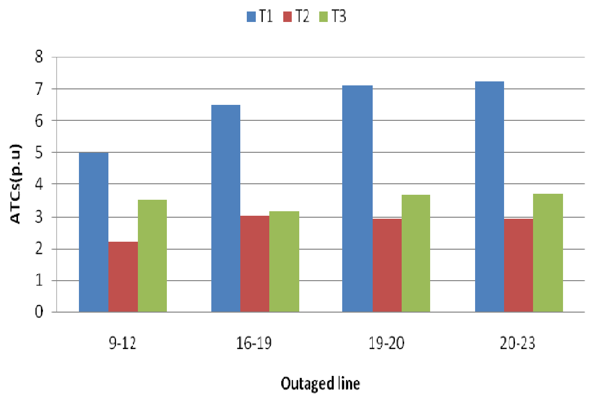

Fig. 2 ATCs with line contingency case for different transactions

ATC with ZIP load for bilateral transactions are obtained for different combinations of ZIP load coefficients. It is observed that the ATC changes with the consideration of different combinations and for a combination of p1, p2, p3 and q1, q2, q3 as 0.1, 0.1, and 0.8 at bus 5, ATCs obtained are 7.8885p.u., 3.0334 p.u., and 4.0326 p.u.. for the transactions T1, T2, and T3 respectively. It is observed that ATC values are observed slightly higher with ZIP load.

B. ATC with SVC (without and with Line Contingency Case)

1. ATC with SVC (without Line Contingency Case)

The maximum ATC is obtained with SVC at bus 6 and is given in Table I. It is observed that the ATC enhances with SVC. The impact of change in location has also been obtained for the ATC and is shown in Fig. 3. It is observed that with SVC location at bus 6, ATC is found higher for all transactions. ATC is found to increase with SVC for all transactions corresponding to case without SVC.

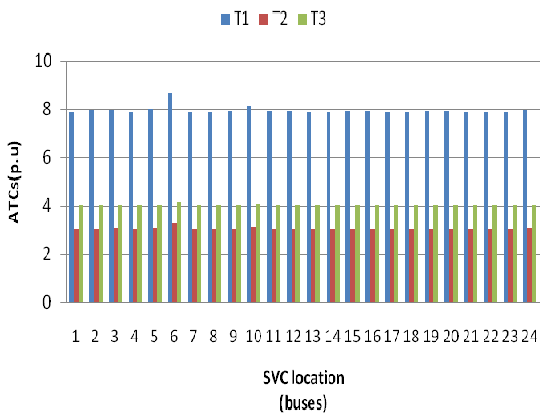

Fig. 3 ATC with SVC for different transactions

2. ATC with SVC (with Line Contingency Case)

With different line contingency cases, the ATC obtained with SVC for all transactions has been obtained and is found maximum with SVC at bus 6 for all transactions cases and is given in Table II. It is observed that the ATC enhances for all the cases of line contingencies and different transactions when compared with the case without SVC (Table I). The ATC corresponding to different locations of SVC for line contingency cases are also obtained and are shown in Figs. 4 (a) to (c). It is observed that with SVC optimal location at bus 6, the ATC is found higher for all transactions and all line outage contingencies. ATC is found to increase with SVC for all transactions corresponding to case without SVC. Thus, the SVC has considerable impact on enhancement of ATC for all transaction cases.

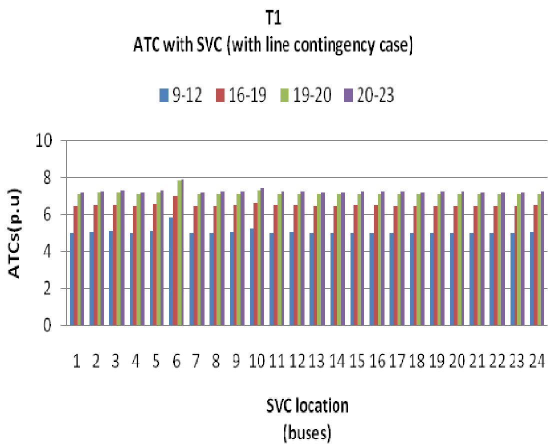

Fig. 4 (a) ATC with SVC for transaction T1

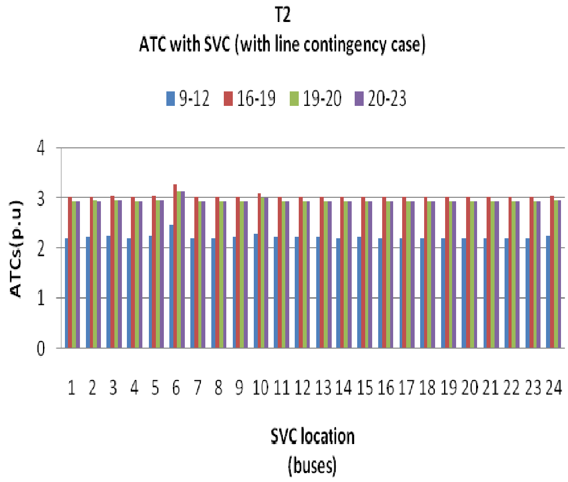

Fig. 4 (b) ATC with SVC for transaction T2

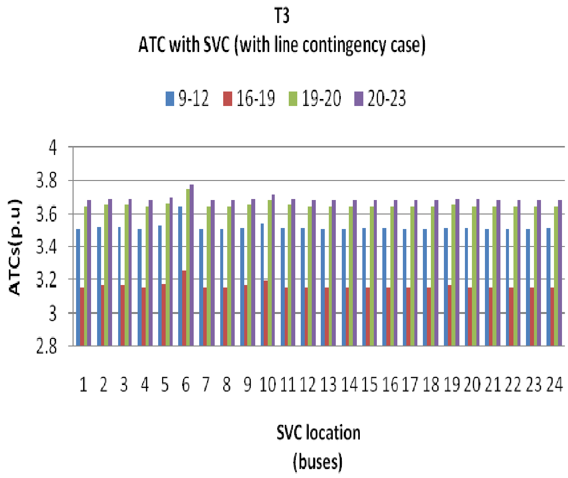

Fig. 4 (c) ATC with SVC for transaction T3

3. ATC with SVC (with ZIP load) and Impact of Location Change

In a ZIP load case, the ATC with SVC has been determined and is observed maximum at for a combination of p1, p2, p3 and q1, q2, q3 as 0.1, 0.1, and 0.8 at bus 5, ATCs obtained are 8.5044 p.u., 3.2281 p.u. and 4.12609 p.u..for the transactions T1, T2, and T3 respectively. The ATC enhancement with SVC is also obtained with ZIP load. However, with the ZIP load, the ATC is observed lower compared to the case without ZIP load. The ATC with 34 different combinations of ZIP load coefficients and change in location has also been obtained for all transactions cases and is shown in Figs. 5 (a) to (c). At bus 6, the ATC enhancement has been observed maximum with SVC for all transaction cases.

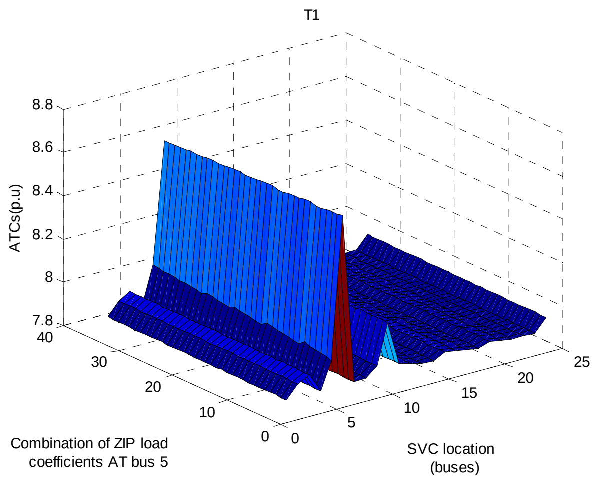

Fig. 5 (a) ATC with SVC and ZIP load at bus 5 for transaction T1

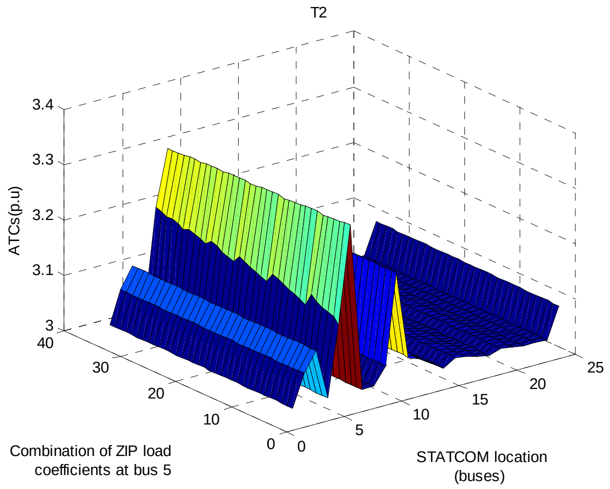

Fig. 5 (b) ATC with SVC and ZIP load at bus 5 for transaction T2

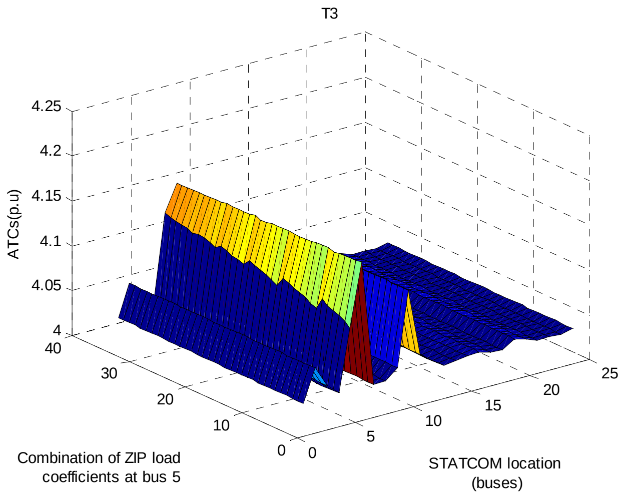

Fig. 5 (c) ATC with SVC and ZIP load at bus 5 for transaction T3

C. ATC with STATCOM without and with Contingency Case

The ATC obtained with STATCOM for all transactions has been obtained and are given in Table I with STATCOM at bus 6. The ATC enhances with STATCOM for all transaction cases and is observed higher compared to with SVC. With the change in location of STATCOM, the ATC are also obtained and are shown in Fig. 6. It is observed that with STATCOM location at bus 6, the ATC is found higher for all transactions.

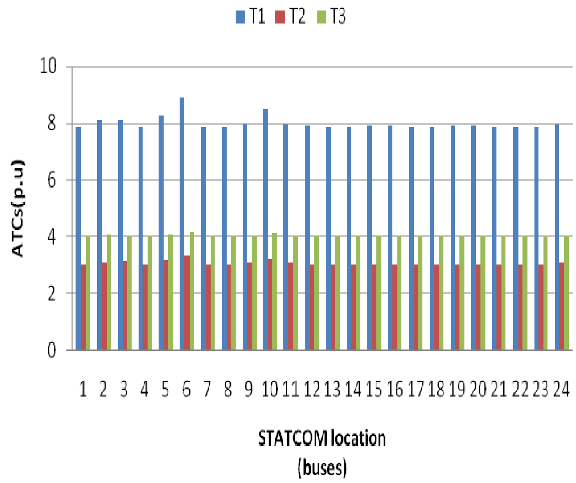

Fig. 6 ATC with STATCOM for different location

D. ATC with STATCOM (with Line Contingency Case)

The ATC has been obtained with STATCOM for all line contingency cases and are given in Table II. It is observed that the ATC obtained with STATCOM enhances for all transactions corresponding to different contingency cases and is observed higher than SVC for all transaction cases and line outages. It is observed that with STATCOM location at bus 6, ATC is found higher for all transactions and line outage contingencies. ATC is found to increase with STATCOM for all transactions corresponding to case without STATCOM. STATCOM has considerable impact on enhancement of ATC for all transaction cases. With the change in location of STATCOM, the ATC has also been obtained for all transaction cases and is shown in Figs. 7 (a) to (c).

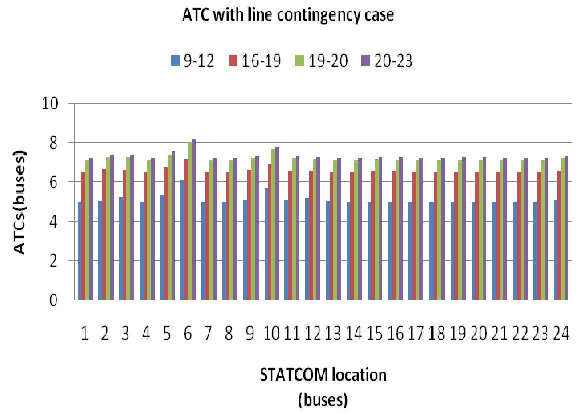

Fig. 7 (a) ATC (p.u) with STATCOM (with line contingency case)

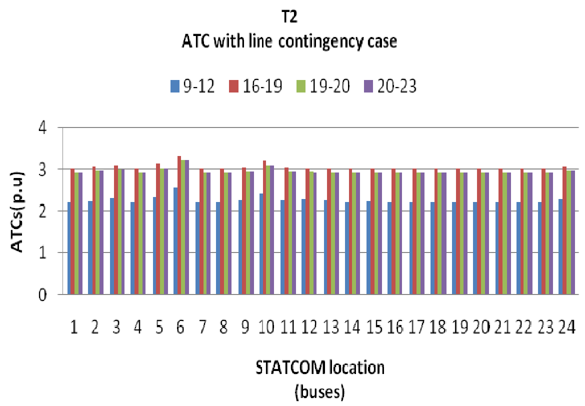

Fig. 7 (b) ATC ATC (p.u) with STATCOM (with line contingency case)

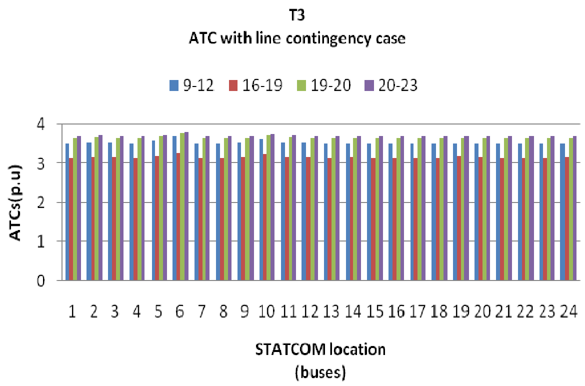

Fig. 7 (c) ATC ATC (p.u) with STATCOM (with line contingency case)

1. ATC with STATCOM with ZIP Load

In a ZIP load case, the ATC with STATCOM has been determined and is observed maximum at bus 10 for a combination of ZIP load coefficients p1, p2, p3 and q1, q2, q3 as 0.8, 0.1, and 0.1 at bus 5, and the ATCs obtained are 8.6728 p.u., 3.2810 p.u. and and 4.1278 p.u.. for the transactions T1, T2, and T3 respectively. It is observed that The ATC enhancement with SVC is also obtained with ZIP load. The ATC with 34 different combinations of ZIP load coefficients and change in location has also been obtained for all transactions cases and is shown in Figs. 8 (a) to (c). At bus 6, the ATC enhancement has been observed maximum with STATCOM for all transaction cases.

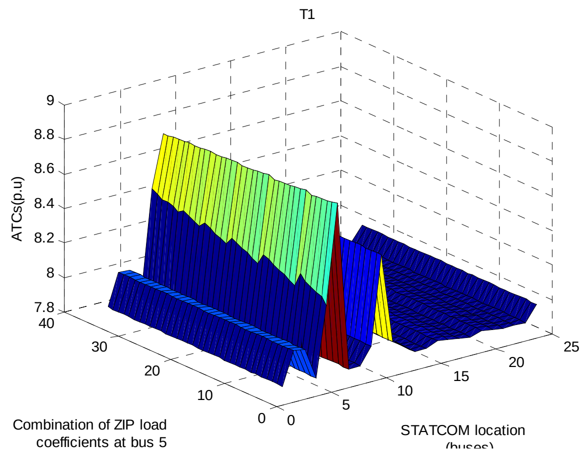

Fig. 8 (a) ATC with STATCOM for transaction T1

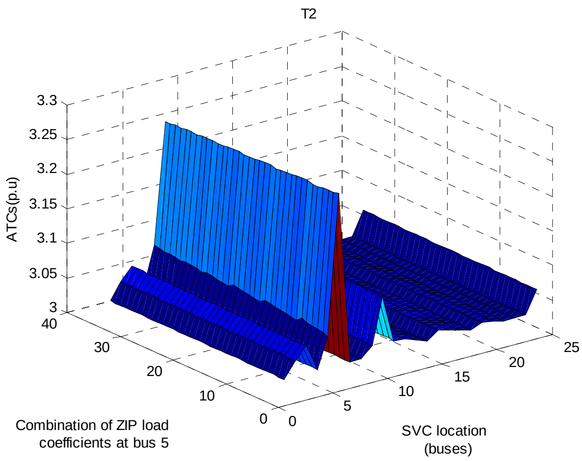

Fig. 8 (b) ATC with STATCOM for transaction T2

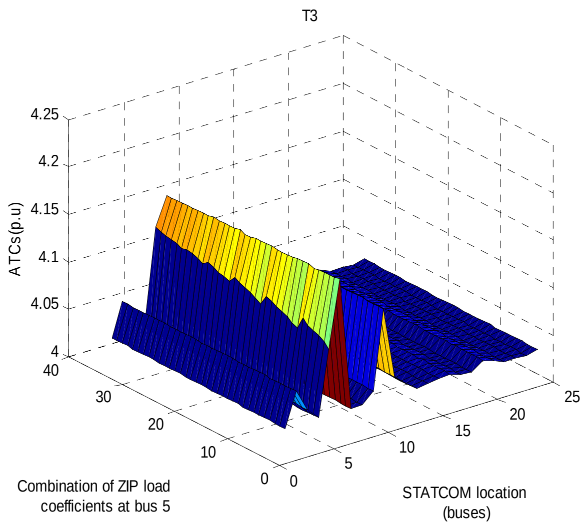

Fig. 8 (c) ATC with STATCOM for transaction T3

TABLE II
ATC (P.U.) WITH SVC AND STATCOM AND LINE CONTINGENCIES

ATC (p.u.) with line contingency cases with SVC				
	9-12	16-19	19-20	20-23
SVC at bus 6 (T1)	5.8399	7.0173	7.8198	7.9559
SVC at bus 6 (T2)	2.4742	3.2612	3.1633	3.1634
SVC at bus 6 (T3)	3.6438	3.2556	3.7556	3.7829
ATC (p.u.) with line contingency cases with STATCOM				
Line outage	9-12	16-19	19-20	20-23
STATCOM at Bus 6	6.1100	7.1474	7.9996	8.1419
STATCOM at Bus 6	2.5530	3.3107	3.2164	3.2167
STATCOM at Bus 6	3.6845	3.2805	3.7806	3.8077

V. CONCLUSION

An optimal power flow based approach for ATC determination for both bilateral and simultaneous transactions have been presented without and with FACTS devices. ZIP load model have also been incorporated in an OPF model for the ATC determination. Different combinations of coefficients of ZIP load have been considered to find an impact on the ATC without and with FACTS devices. The impact of change in location of FACTS devices has also been studied. Based on the results obtained, it is concluded that the ATC increases in the presence of FACTS devices for all types of transactions. With change in the location of FACTS devices, the ATC values changes and are observed maximum at only optimal locations. With variation in the ZIP load coefficients and location of FACTS devices, the ATC changes showing the impact of location and ZIP load. The ATC in case contingencies decreases and with FACTS devices it is found to increase in all transactions without and with ZIP load model.

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Ashwani Kumar graduated from Pant Nagar University in Electrical Engineering in 1988, masters’ from PEC Chandigarh in 1994 in honors and Ph.D. in 2003 from IIT Kanpur. He is working as Professor in the Department of Electrical Engineering at NIT Kurukshetra. His research interests are in power system restructuring issues, distributed generation, renewable sources integration, and demand side management.

Jitender Kumar did his masters in Power Systems from NIT Kurukshetra and is presently pursuing his Ph.D program at IIT Roorkee, India. His research interests include ATC determination and enhancement using FACTS devices.