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Impact of Different Types of Transactions on ATC Enhancement with IPFC

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ABSTRACT

In the present era, demand of energy supply is increasing as the time passes by, therefore existing power transfer network needs to be widen up throughout the world and complete use of this power system network should be made so that congestion in the network can be reduced. In order to avoid this problem, Available Transfer Capability (ATC) of the transmission network and loadability factor should to be defined in advance for a day-ahead market so that load carrying capabilities of existing transmission grid can be enhanced. Besides this, load carrying and power transfer capabilities of present network can be improved by incorporating power flow controllers in the system which reschedules the power flows in the existing grid. ATC is computed with Interline Power Flow Controller (IPFC) by considering Optimal Power Flow (OPF) based approach in this paper. The impact of various bilateral and multilateral transactions has been evaluated on taking IEEE 24 bus test system. The results have been obtained for the same by varying the locations of IPFC in the network and ATC found to be increased with IPFC for multilateral transaction cases.

Keywords

Optimal Power Flow (OPF); Available Transfer Capability (ATC); loadability; IPFC.

INTRODUCTION

In a deregulated market environment, competition is increasing day by day for trading electricity. Therefore, power sector utilities are supplying electricity throughout the globe and they are running on a way so as to completely exploit their present power supplies in the best possible way. Existing power system network can be utilized effectively and securely in order to improve the efficiency of system by including power flow controllers in test system.

The inclusion of Flexible Alternating Current Transmission System (FACTS) in the power system networks has been increased worldwide because FACTS device paves way for new opportunities of controlling the power flow, increasing the usable capacity of present lines and enhancing ATC [1]-[4]. Since these controllers are composed of self-commutated inverters, therefore ATC of the system can be enhanced without establishing new transmission lines in the present grid. These devices are not only effectively increasing the potential of present transmission system but also enhances ATC, increases its control and operation, avoids congestion and provides better reliability to the system.

Many researches have been made towards increasing power transfer capability of transmission grid when power flow controllers were incorporated in the system. Effective role of FACTS controllers after privatization in electricity sector are explained by N.G. Hingorani [5]. Many of the FACTS devices were introduced in virtual test systems for analyzation purpose. Impact of UPFC on ATC enhancement has been evaluated in [6]. Two power system models were taken for illustration and ATC is evaluated by PTDF method. It is found from the results that transfer capability of the system has been enhanced to deliver less

expensive power supply to the customers. M. I. Alomoush [7] has applied dc based approach to determine various contributions of users and UPFCs to transmission grid. Its impact on line power flows and transmission line usage has been analyzed. N. Schnurr [8] has applied a sensitivity analysis based on GSDF and PIM for effectively enhancing its power transfer capability by including FACTS in the system. However, LFC controllers were installed in the network for various contingency cases to enhance ATC of the system. H. Farahmand in [9] discussed about ATC enhancement by incorporating SVC in the 9-bus test system considering Repeated Power Flow (RPF) technique and genetic algorithm optimization method has been implemented for finding the best suitable location of SVC in proposed test network. Impact of thermal limits on ATC determination has been seen in [10]. Various security and economic limits are taken into consideration for ATC calculation [11] and output power changed according to economic dispatch method. One step DC method was used for determining ATC of the system and results are obtained with faster convergence when GA technique is applied to the system [12]. B.V. Manikandan [13] has calculated multi area ATC in Combined Economic Emission Dispatch scenario by applying ACPTDF and PF methods. Line contingency cases are also considered for calculation purpose and it is found that OTDF method gave the accurate result for this case.

In this paper, ATC has been calculated with IPFC by applying OPF methodology because it can easily incorporate large number of constraints and give result of substantial accuracy. The model of IPFC (FACTS device) has been discussed from a static point of view. ATC is determined by considering IPFC in the system for different bilateral and multilateral/simultaneous transaction cases. It is found that when IPFC is present in the network at optimal location, ATC and voltage profiles of the system have been improved.

Paper is organized in the following manner: Firstly, problem is formed using OPF technique used for ATC calculation with IPFC. Then static modeling of IPFC is detailed. Results are analyzed through simulation and ATC found to be enhanced for various transactions taken into consideration and lastly paper is concluded in brief.

PROBLEM FORMATION

A. OPF based technique

Generally problem for OPF method can be framed as:

$$\text{Min } N(y,u,m,\psi facts) \qquad (1)$$

Subjected to the constraints below:

$$t(y,u,m,\psi facts)=0 \qquad (2)$$

$$u(y,u,m,\psi facts)\leq 0 \qquad (3)$$

Where,

y = state vector,

u = controlling parameter,

m = parameter having fixed value,

N = Objective function,

t, *u* = Equality and inequality constraints respectively,

ψfacts = parameter which controls FACTS devices.

For ATC determination with IPFC, the necessary parameters can be incorporated in the problem according to the variables taken into consideration.

B. ATC computation

Transactions either bilateral or simultaneous considered for the calculation purpose can be maximized by objective function given below:

$$\text{Max } \lambda_M = \sum_{R=1}^{a} \lambda_R = \sum_{S=1}^{b} \lambda_S \qquad (4)$$

For bilateral type transaction case, one set of transaction are taken for study whereas for multilateral type transaction case, multiple sets of power transaction between *a* and *b* buses have been considered.

Where *a*, *b* are seller and buyer buses respectively.

(i) Equality Constraints-

The power injection equations (active and reactive) examined from Newton-Raphson (N-R) load flow method at bus *i* are shown below:

$$P_i(V,\delta) = \sum_{j=1}^{k} V_i V_j [G_i \; sin(\delta_i) - B_i \; cos(\delta_i)] \quad (5)$$

$$Q_i(V,\delta) = \sum_{j=1}^{k} V_i V_j [G_i \; cos(\delta_i) - B_i \; sin(\delta_i)] \quad (6)$$

Where,

P_i, Q_i= MW and MVAr power injected at some bus *i*,

k = number of buses,

G_i , B_i = conductance and susceptance matrices respectively.

Power injection equations ($P_i$and Q_i) for maximum loadability factor have been transformed as:

$$P_i = \lambda_M * P_G - \lambda_M * P_D \quad (7)$$

$$Q_i = Q_G - Q_D \quad (8)$$

For simultaneous transaction case, power injection equations at generation and demand buses (*a* and *b*) are modified as below:

$$P_{G\ 1} = \lambda_{a1} P^0_{Ga1};\ P_{G\ 2} = \lambda_{a2} P^0_{G\ 2} \ldots = \lambda_a\ P^0_G \quad (9)$$

$$P_{D\ 1} = \lambda_{b1} P^0_{D\ 1};\ P_{D\ 2} = \lambda_{b2} P^0_{D\ 2} \ldots = \lambda_b\ P^0_D \quad (10)$$

Where, Re=*a1*, *a2*,…,*aa* are parameters for seller buses,

Se=*b1*, *b2*,…,*bb* are parameters for buyer buses.

It is analyzed from above equations that for increase in generation at bus *a*, there are corresponding increase in load at bus *b*.

(ii) Inequality constraints- Various inequality constraints are detailed as follows:

Voltage limits: Voltage of the given system should lie in a standard range of minimum to maximum limits i.e. 0.95 to 1.05 p.u.

$$V_{i\,m} < V_i < V_{i\,m} \quad (11)$$

Angle limits: Angle of the given system should lie in a standard range of minimum to maximum limits i.e. -0.2531 to 0.2531 radian.

$$\delta_{i\,m} < \delta_i < \delta_{i\,m} \quad (12)$$

Power generation limits (real and reactive):

There is a limit to MW and MVAr power generations of the connected generators in the system.

$$P_{G\ m} < P_G < P_{G\ m} \quad (13)$$

$$Q_{G\ m} < Q_G < Q_{G\ m} \quad (14)$$

Line flow (active and reactive) limit: There is a maximum line flow limit in each line at sending and receiving ends for controlling its flow.

$$P_{i\ m} < P_i < P_{i\ m} \quad (15)$$

$$Q_{i\ m} < Q_i < Q_{i\ m} \quad (16)$$

Where,

P_D ,Q_D : MW and MVAr load demands at bus *i*,

P_G , Q_G : MW and MVAr power generations at bus *i*,

V_i, δ_i: Voltage and angle of corresponding bus i,
$P_{G\ m}$, $P_{G\ m}$: Maximum and minimum MW power generations,
$Q_{G\ m}$, $Q_{G\ m}$: Maximum and minimum MVAr power generations,
$P_{ij\,m}$, $P_{i\ m}$: Maximum and minimum MW power flow between buses *i* and *j*,
$Q_{i\ m}$, $Q_{i\ m}$: Maximum and minimum MVAr power flow between buses *i* and *j*,
MW, MVAr: Real and reactive powers.

In order to calculate ATC in the present test network, power generation and demand at respective *a* and *b* bus changes according to the transactions considered and given as below:

$P_G = \lambda P_G^0$ (17)

$P_D = \lambda P_D^0$ (18)

Where,

P_G , P_D = power generation and demand at buses *a* and *b* respectively.

ATC can be computed by the following equation:

ATC = $\lambda_m \quad P_D^0 - P_D^0$ (19)

Following procedure is adopted for ATC determination with IPFC:

- Initially load flow calculations are done by N-R method.
- Then selection of different power transaction taking place between a and b buses is done.
- ATC is obtained by interfacing MATLAB and GAMS.
- IPFC is included in the system by considering its static equivalent model.

ATC enhancement is examined for different transaction cases on varying locations of IPFC in the system.

STATIC MODELING OF INTERLINE POWER FLOW CONTROLLER (IPFC)

IPFC is designed by connecting *n* no. of inverters simultaneously at their common dc link whereas each of them work as SSSC to give series reactive compensation for their respective lines in which they are connected. Direct Current (DC) terminal is provided for transferring active power between them. Thus, IPFC has the ability to give MW as well as MVAr power compensation for few of the lines and therefore utilize the transmission network up to their maximum potential. Stability in power system can be enhanced by introducing FACTS controllers like IPFC in the network. The static modeling of IPFC can be done by connecting no. of series reactive compensators SSSC together in the structure through common dc terminals. A simple form of IPFC is considered for study purpose which comprises of two series reactive compensators connected in two transmission lines for controlling the power flow of two lines and two voltage sources are injected in series with them for controlling real power flow of the line. Its equivalent static model is shown in Fig 1. The power injection equations for the given equivalent structure of IPFC are as below.

$P_i = V_i^2 G_{ii} + \sum_n V_i V_n (G_{i} \cos\delta_{i} + B_{i} \sin\delta_{i}) + \sum_n V_i V_{s,i} [G_{i} \cos(\delta_i - \delta_{s,i}) + B_{i} \sin(\delta_i - \delta_{s,i})]$ (20)

$Q_i = -V_i^2 B_{ii} + \sum_n V_i V_n (G_{i} \sin\delta_{i} - B_{i} \cos\delta_{i}) + \sum_n V_i V_{s,i} [G_{i} \sin(\delta_i - \delta_{s,i}) - B_{i} \cos(\delta_i - \delta_{s,i})]$ (21)

$P_n = V_n^2 G_n + V_i V_n (G_{i} \cos\delta_n + B_{i} \sin\delta_n) + V_n V_{s,i} [G_{i} \cos(\delta_n - \delta_{s,i}) + B_{i} \sin(\delta_n - \delta_{s,i})]$ (22)

$Q_n = -V_n^2 B_n + V_i V_n (G_i \cos\delta_i - B_i \sin\delta_i) + V_i V_{s,n} [G_{i} \cos(\delta_i - \delta_{s,n}) - B_{i} \sin(\delta_i - \delta_{s,i})]$ (23)

Real $P_{e\ \ ha}$ through common DC terminal = zero.

$P_{e\ \ ha} = R\ (\sum_n V_{s,i}\ I_n^*) = 0$ (24)

$\sum_n [V_i V_s\ [G_{ii} \cos(\delta_i - \delta_{s,i}) - B_{i} \sin(\delta_i - \delta_{s,i})] + V_n V_s\ [G_{i} \cos(\delta_n - \delta_{s,i}) - B_{i} \sin(\delta_n - \delta_{s,i})]] = 0$ (25)

Where, $G_{ii} = \sum_n G_{i}$; $B_{ii} = \sum_n B_{i}$

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Where, $n = j, k, \ldots$

Series injected voltage source have following limits:

$$V_{s\ ,i:\ m} < V_{s\ ,i:} < V_{s\ ,i:\ m} \quad (26)$$

$$\delta_{s\ ,i:\ m} < \delta_{s\ ,i:} < \delta_{s\ ,i:\ m} \quad (27)$$

Where, $n = j, k, \ldots$

ATC calculation can be done with IPFC on applying above equations in OPF based approach.

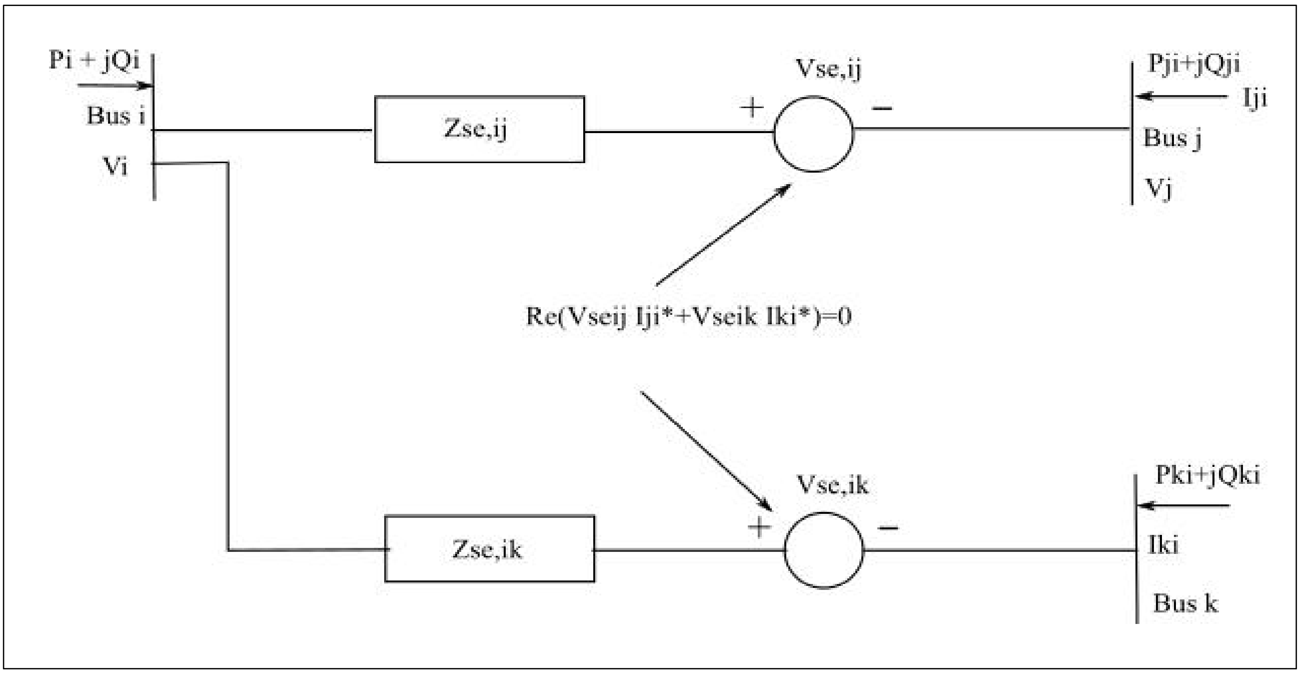

Fig 1: Equivalent static model of IPFC

ANALYSIS OF RESULTS

ATC is calculated with IPFC by including its power flow equations in OPF based technique. OPF methodology is nonlinear in behavior therefore CONOPT solver (nonlinear programming solver) of GAMS 23.4 is called in MATLAB for determining ATC. Table 1 is representing the values of ATC obtained on varying the line locations of IPFC in the test system for various bilateral transactions. Different line locations have been taken in the network for monitoring their impact on ATC enhancement. It is been observed from Table 1 and Fig 2 that optimum value of ATC is obtained at line location no. 4 for bilateral transactions and upcoming line location having maximum value of IPFC in the system found to be at line no. 12. Thus, the location at which ATC has maximum value is said to be the optimal location of compensator in the transmission system.

A. ATC with IPFC for bilateral transaction cases

T1: bilateral power transaction occurring between *a1* and *b1*.

T2: bilateral power transaction occurring between *a2* and *b2*.

T3: bilateral power transaction occurring between *a3* and *b3*.

Where, *a1*=23, *a2*=21 and *a3*=10 are seller buses,

b1=18, *b2*=15and *b3*=9 are buyer buses.

Table 1. ATC for various line locations of IPFC

Different Line Locations	ATCs (p.u.) obtained on incorporating IPFC		
	T1	T2	T3
4	**10.4544**	**12.3553**	**3.6748**
6	9.4936	11.1583	3.2937
12	**9.9777**	**11.7543**	**3.4164**
14	9.6191	11.3171	3.2168
16	9.4511	11.3810	3.2670
18	9.7017	11.5899	3.3118
20	9.7953	11.3906	3.3721
24	9.4529	11.4148	3.1768
25	9.4296	11.3479	3.2141
26	9.5695	12.4298	3.3615
28	9.4772	11.9187	3.2166
30	9.4026	11.1319	3.1766
32	9.3854	11.1934	3.1820
34	9.5566	11.1090	3.1953
36	9.4133	11.1276	3.1743

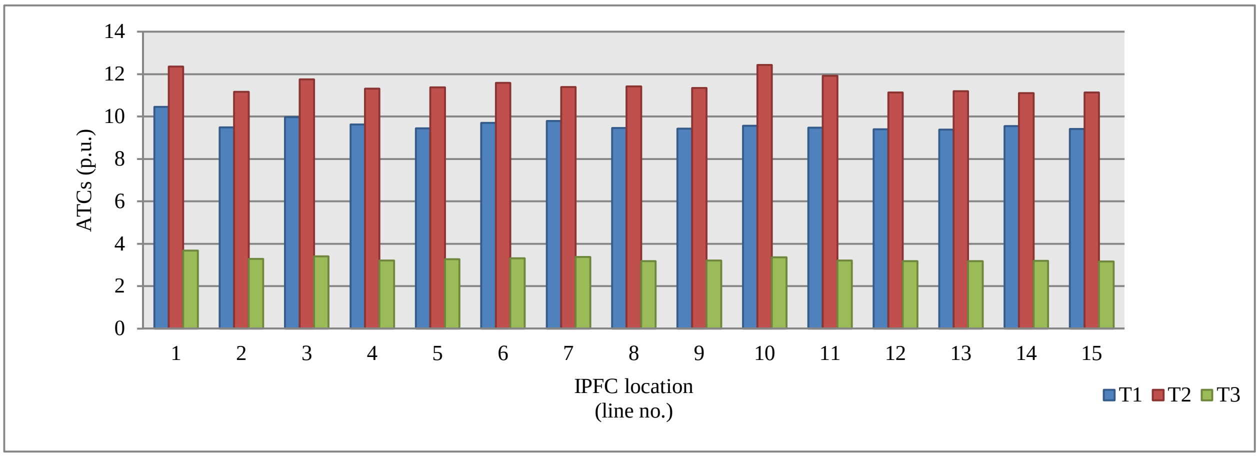

Fig 2: Available Transfer Capability (p.u.) for various locations of IPFC

B. ATC with IPFC for multilateral transaction cases

Two different multilateral/simultaneous transaction cases have been taken into consideration and their impact on ATC enhancement have been evaluated when IPFC is included in the present 24 bus test system. Different multilateral transactions are detailed as follows:

T4: Simultaneous power transaction occurring between *a4* and *b4*.

T5: Simultaneous power transaction occurring between *a5* and *b5*.

Where, *a4*=23 and 21, *a5*=16 and 1 are seller buses,

b4=18 and 15, *b5*=20 and 10 are buyer buses.

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Table 2 is showing that ATC is obtained on varying line locations of power flow controller in the present system for two simultaneous transaction cases. ATC (p.u.) value computed for various line locations of IPFC is shown in Fig 3 and Table 2. The strategic locations are obtained at line location no. 4 for T4 whereas at line no. 14 for T5 and upcoming best locations are at line no. 12 for T4 transaction and at line no. 28 for T5 transaction case.

Table 2. ATC for various line locations of IPFC

Different Line Locations	**ATCs (p.u.) obtained on incorporating IPFC**	
	T4	T5
4	**23.7144**	8.0280
6	19.4600	8.5286
12	21.6488	8.0954
14	19.8269	**9.6227**
16	20.1727	8.5097
18	20.3362	8.4465
20	20.6641	8.9634
24	19.2303	8.6700
25	19.6936	8.4393
26	21.4058	9.0722
28	19.2975	9.1671
30	19.2132	9.1535
32	19.0412	8.8639
34	19.4101	8.5610
36	19.1667	8.5563

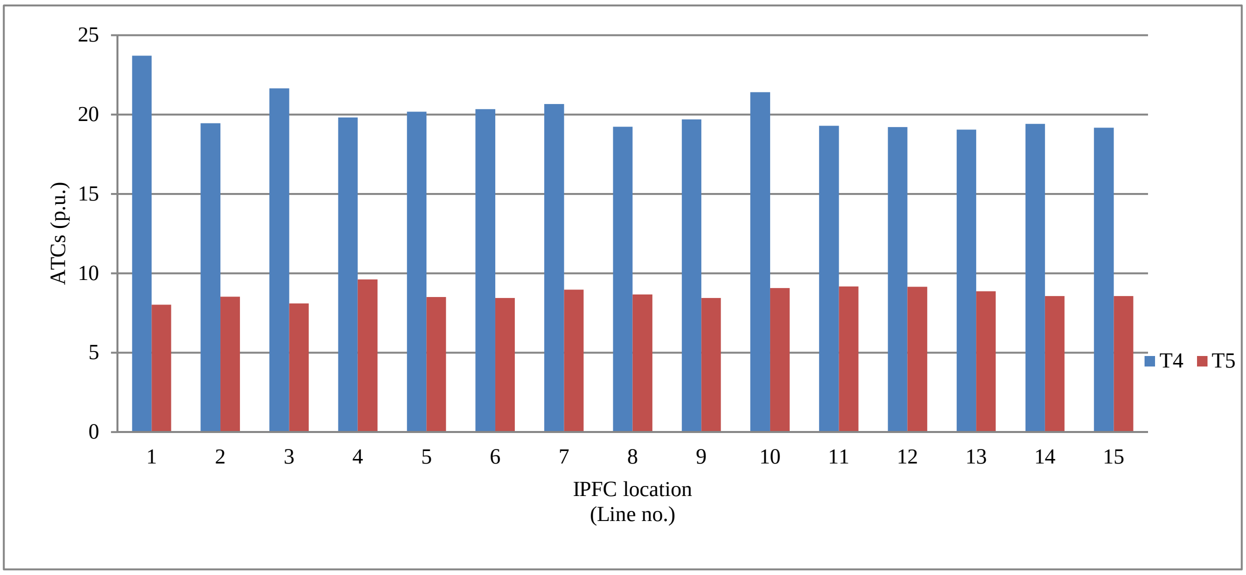

Fig 3: Available Transfer Capability (p.u.) for various locations of IPFC

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On analyzing the value of ATC obatined for different locations of IPFC in the present test system, it is found that this device is suitably placed in the network where consumption of reactive power is minimum and system remains within its stability limits to reduce the problem of congestion.

Whereas locations in Fig 2 and Fig 3 numbered from 1-15 are detailed in Table 3:

Table 3. Various line locations of IPFC in graph

Line locations of IPFC in graph	Line locations of IPFC in the network
1	4
2	6
3	12
4	14
5	16
6	18
7	20
8	24
9	25
10	26
11	28
12	30
13	32
14	34
15	36

The active power flows are obtained on including IPFC in test system for various bilateral and simultaneous transaction cases as shown in Fig 4 and Fig 5. Line flows are found to be different for all bilateral and multilateral transaction cases with IPFC and line 7-8 is approaching towards its line limit i.e. 1.75 p.u. for each transaction case.

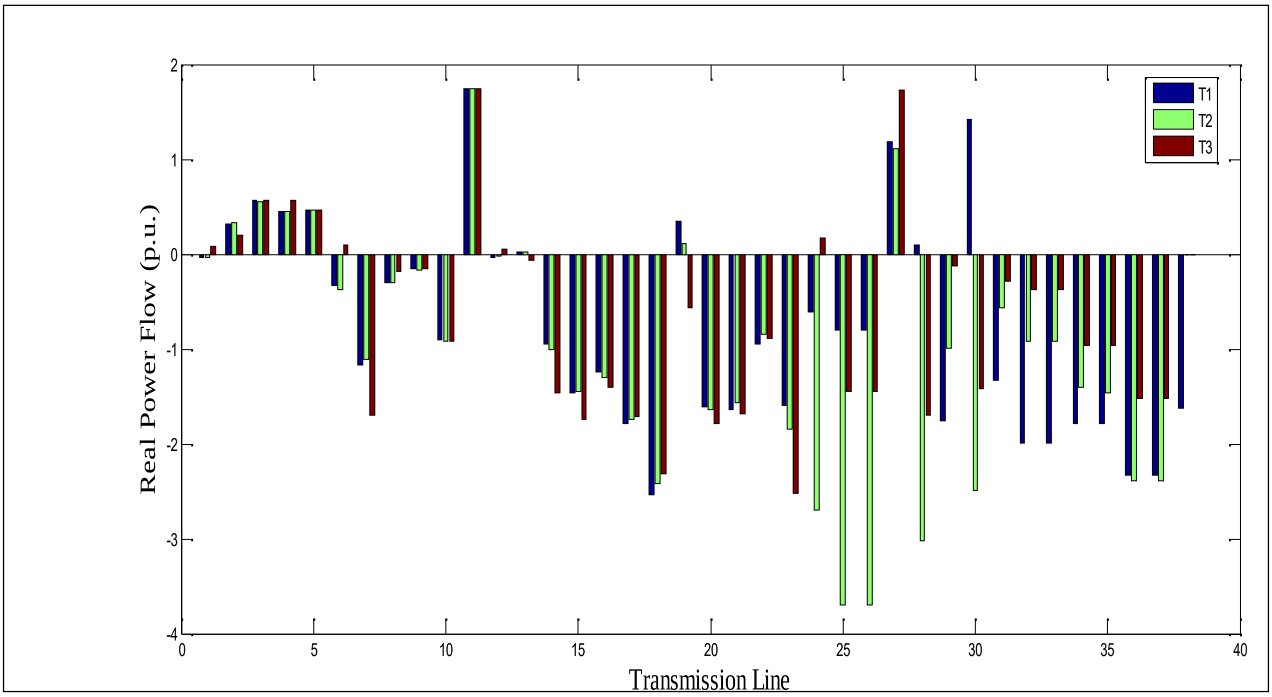

Fig 4: Real power flow (p.u.) with IPFC for bilateral transactions

Solving for various transactions give a detailed picture of ATC variation. Values of ATC have been calculated by OPF method for bilateral and simultaneous transaction cases. Loadability factor, real and reactive power flow losses are also calculated for all transactions. It has been observed from Table 4 that loadability factor has increased for multilateral transaction case as compared to bilateral transaction case and corresponding MVAr losses for that transaction case have been decreased.

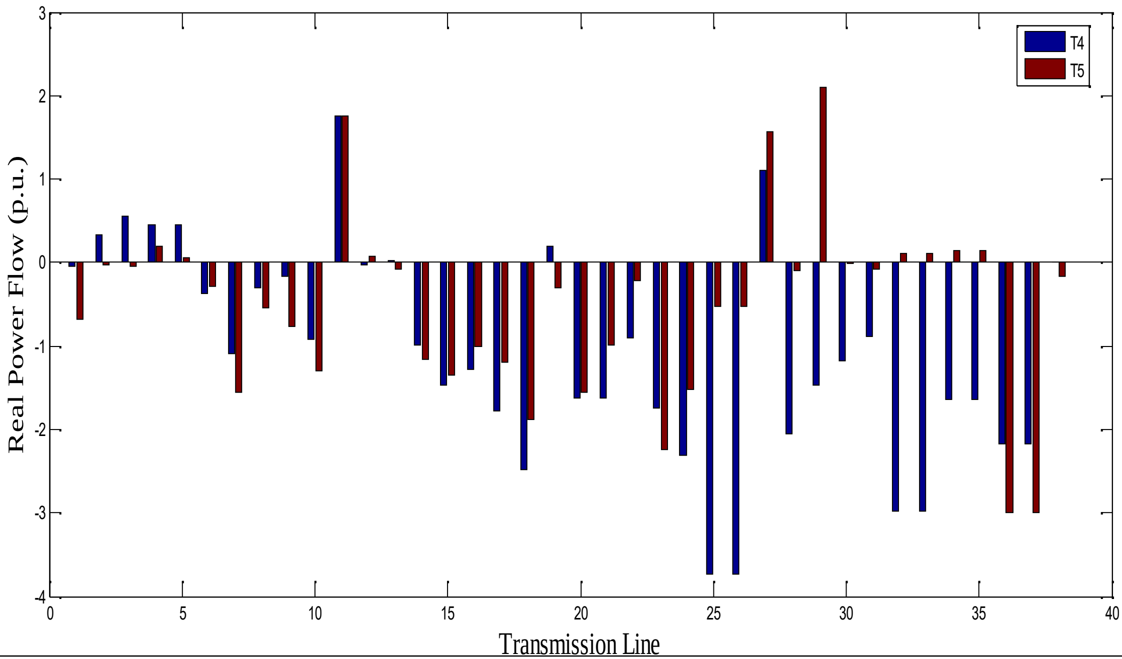

Fig 5: Real power flow (p.u.) with IPFC for multilateral transactions

Table 4. Loadability factor and power flow losses for various transactions

Different Transactions	Loadability Factor	MW Losses (p.u.)	MVAr Losses (p.u.)
23-18 (T1)	2.8268	0.4207	-2.1314
21-15 (T2)	3.5103	0.5516	-1.0919
10-9 (T3)	1.8139	0.3617	2.3120
23-18 & 21-15 (T4)	6.0463	0.5843	-0.8561
16-20 & 1-10 (T5)	4.3878	0.3095	-2.7125

It has also been observed from Table 4 that loadability factor is more for T2 transaction case among bilateral type of power transactions and for T4 among multilateral type of transaction cases.

CONCLUSION

This paper presents ATC determination with IPFC by taking different bilateral and simultaneous transaction cases between generation as well as demand buses on applying OPF technique. The impact of all of the transaction cases on ATC enhancement with IPFC and loadability factor of the system has been evaluated. On analyzing the results, it is revealed that ATC value has enhanced for strategic placement of IPFC in the system for all bilateral and multilateral transaction cases. Optimal location of IPFC has been

determined iteratively on varying the same for different line locations. Enhancement in the value of ATC and loadability factor is found for multilateral transactions as compared to bilateral transaction cases.

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