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ACPTDF for Multi-transactions and ATC Determination in Deregulated Markets

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Abstract

Available transfer capability in the transmission network has become essential quantity to be declared well in advance for its commercial use in a competitive electricity market. Its fast computation using DC load flow based approach is used worldwide for on line implementation. Many authors have proposed the ATC calculation based on DC/AC load flow approach. In this paper, AC PTDF based approach has been proposed for multi-transaction cases using power transfer sensitivity and Jacobian calculated with three different methods. The methods can be implemented for any number of transactions occurring simultaneously. The results have been determined for intact and line contingency cases taking multi-transaction/simultaneous as well as single transaction cases. The main contributions of the paper are: (i) ATC determination for multi-transactions environment, (ii) ATC determination and comparison with three approaches of PTDF calculations, (iii) LODFs with line contingency cases for multi-transaction environment and thereby ATC determination. The results have also been obtained with DC method for comparison. The proposed method have been applied for IEEE 24 bus RTS.

Keywords: *Available transfer capability, AC load flow, AC power transfer distribution factors , line outage contingency, line outage distribution factors, multi-transactions, simultaneous transactions.*

1. Introduction

The bulk power transactions are limited by the transmission system security and stability, and it is the responsibility of the system operators (SOs) to control the power transactions and overloading of the transmission network beyond their thermal loading and megavolt-amperes (MVA) limits. For this, SO has to update real-time index termed as available transfer capability (ATC). A 1996 report of North American Electrical Reliability Council (NERC) establishes a framework for determining ATC of the interconnected transmission networks for a commercially viable wholesale market [1-2].The assessment of transmission system loadability play a vital role in both operational planning and real time operation in order to the best utilization of the available system components with regard to system security. The system loadability determination for the secure operation of the system with line thermal limits, steady state stability limit, transient stability limits, and voltage stability limits has been well reported in the literature. The well-known techniques of maximum loadability determination focus on quantification of the distance of the system state from the maximum loadability boundary. The methods to quantify the system security are continuation power flow based, direct methods and energy methods [3-8].

The electric power industries, all over the world, have been changing to a new deregulated environment due to many forces to create competitive electricity markets [9-10]. With the introduction of competition in the power industry, there has been a search for the better utilization of the transmission facilities. Thus, the transfer capability across the transmission system is often used as a basis to determine the quantity of firm transmission service available to reschedule energy delivery. In deregulated electricity markets, ATC of a transmission system has emerged as a new measure. Under the U. S. Federal Energy Regulatory Commission (FERC) orders 888 and 889, which established open access nondiscriminatory transmission services policy and open access same time information system (OASIS), ATC is required to be posted on OASIS to make competition reasonable and effective [11]. Such information will help power marketers, sellers and buyers in reserving transmission services. Utilities must therefore, determine their ATC adequately to ensure the security of the system while serving a wide range of transmission transactions. ATC has to be continuously updated and posted following changes in the system conditions or scheduled power transfers between the areas [11]. There are various sources of uncertainties involved in the ATC calculation [12]. These uncertainties can be attributed to weather conditions, forced and scheduled transmission outages, and generation unavailability. A number of software tools, such as continuation power flow (CPFLOW) [14], transmission and voltage limitation program (TVLIM) [13] and TRACE [15] have been developed for transfer capability calculation. The dynamics of the system, when subjected to small and large disturbances, has to be studied and analyzed for determination of ATC [16-18]. However these methods are time intensive for on line implementation.

The other methods based on Power Transfer Distribution Factors/Outage Factors (PTDFs), (LODFs) using DC load flow and AC load flow approach for ATC determination using the sensitivity based approaches has been reported in [16-28]. The DC load flow based methods utilizing DC power transfer distribution factors are reported for ATC computation in [21]. The ACPTDFs based approach with line contingency cases has been presented in

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[28]. Many authors utilized sensitivity based methods for computation of ATC [22-27]. The methods were presented for bilateral transactions cases.

Based on the literature survey, authors have determined ATC for single transaction cases with distribution factors based approach, however, simultaneous or multi-transactions cases have not been accounted for ATC determination with intact case as well as line contingency cases using power transfer distribution factors determined under intact and line contingenct cases. Since in a multi-lateral deregulated electricity market environment, multi-transactions cannot be avoided for ATC determination as it will not give accurate signal to the ISO for its quantification and reservation for further commercial activity.

In this paper, PTDFs based approach using AC load flow has been proposed for ATC determination in case of multi-transactions environment. The line outages have also been considered for ATC determination in multi-transaction cases. The results have also been obtained for single transactions cases. Three approaches have been implemented based on AC load flow for power transfer distribution factors and line outage distribution factors calculations and thereby ATC determination. The main contributions proposed in the present work are: (i) ATC determination for multi-transaction cases, (ii) ATC determination and comparison with three approaches of PTDF calculations based on AC load flow, (iii) LODFs with line contingency cases for multi-transaction environment and thereby ATC determination. The proposed approach can be implemented for any number of tranactions occurring simultaneously in the network. The results have also been obtained for multi-transactions using DCPTDF based approach for line intact and contingency cases for comparison. The results have been obtained for IEEE RTS 24 bus system [30].

2. Methodology for ATC Determination in Case of multi-transactions

For a transaction among the buyer and seller buses by ΔP_{mn} , if the change in the transmission line quantity is ΔP_{ij} , the AC power transfer distribution factors can be defined as,

$$ACPTDF_{ij,mn} = \frac{\Delta P_{ij}}{\Delta P_{mn}} \quad (1)$$

For PTDF calculation using AC load approach, the power flow sensitivity and Jacobian of power injection equations is required. The Jacobian can be calculated using N-R load flow based approach. The power flow equations in polar form can be represented as:

$$P_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}|\cos(\theta_{ij} - \delta_i + \delta_j) \quad (2)$$

$$Q_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}|\sin(\theta_{ij} - \delta_i + \delta_j) \quad (3)$$

Where n be the total no of buses P_i and Q_i are the real and reactive power injected at anybus *i*

$|V_i|, |V_j|$ are the voltage magnitudes at the buses, respectively

δ_i, δ_j are the voltage angles at the buses *i* and bus *j*

$|Y_{ij}|, \theta_{ij}$ are taken from Y_{bus}.

Using Taylor series expansion, the change in power flows at any bus *i* can be formulated in terms of Jacobian as:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} \quad (4)$$

where

$$[J_1] = \frac{\partial P}{\partial \delta}; [J_2] = \frac{\partial P}{\partial |V|}; [J_3] = \frac{\partial Q}{\partial \delta}; [J_4] = \frac{\partial Q}{\partial |V|} \quad (5)$$

The change in the angle and voltage magnitude can be determined as:

$$\begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix}^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{6}$$

Using N-R load flow analysis bus voltage magnitudes and angles can be evaluated. For calculation of ACPTDFs, Jacobian and power flow sensitivity can be calculated.
The power flow sensitivity can be determined using the power flow equations for real power. The real power flow (P_{ij}) in a line-*k*, connected between buses *i* and *j*, can be written as:

$$P_{ij} = V_i V_j Y_{ij} \cos(\theta_{ij} + \delta_j - \delta_i) - V_i^2 Y_{ij} \cos\theta_{ij} \tag{7}$$

Where, V_i and δ_i are the voltage magnitude and angle at bus-*i*. Y_{ij} and Θ_{ij} are magnitude and angle of ij^{th} element of [$\boldsymbol{Y_{Bus}}$].

Using Taylor's series approximation and ignoring higher order terms, change in real power flow can be written as:

$$\Delta P_{ij} = \frac{\partial P_{ij}}{\partial \delta_i}\Delta\delta_i + \frac{\partial P_{ij}}{\partial \delta_j}\Delta\delta_j + \frac{\partial P_{ij}}{\partial V_i}\Delta V_i + \frac{\partial P_{ij}}{\partial V_j}\Delta V_j \tag{8}$$

The sensitivity coefficients appearing in (7) can be obtained using the partial derivatives of real power flow (6) with respect to variables $\boldsymbol{\delta}$ and $\boldsymbol{V}$ as:

$$\frac{\partial P_{ij}}{\partial \delta_i} = V_i V_j Y_{ij} \sin(\theta_{ij} + \delta_j - \delta_i) \tag{9}$$

$$\frac{\partial P_{ij}}{\partial \delta_j} = -V_i V_j Y_{ij} \sin(\theta_{ij} + \delta_j - \delta_i) \tag{10}$$

$$\frac{\partial P_{ij}}{\partial V_i} = V_j Y_{ij} \cos(\theta_{ij} + \delta_j - \delta_i) - 2V_i Y_{ij} \cos\theta_{ij} \tag{11}$$

$$\frac{\partial P_{ij}}{\partial V_j} = V_i Y_{ij} \cos(\theta_{ij} + \delta_j - \delta_i) \tag{12}$$

The sensitivity of power flow equation can be written in the compact matrix form as:

$$\Delta \mathrm{P}_{ij} = \begin{bmatrix} \frac{\partial \mathrm{P}_{ij}}{\partial \delta_2}, \ldots\ldots, \frac{\partial \mathrm{P}_{ij}}{\partial \delta_n} \frac{\partial \mathrm{P}_{ij}}{\partial V_{g+1}}, \ldots\ldots \frac{\partial \mathrm{P}_{ij}}{\partial V_n} \end{bmatrix} \begin{bmatrix} \Delta\delta_2 \\ \vdots \\ \Delta\delta_n \\ \Delta|V_{g+1}| \\ \vdots \\ \Delta|V_n| \end{bmatrix} \tag{13}$$

Where $\begin{bmatrix} \frac{\partial \mathrm{P}_{ij}}{\partial \delta_2}, \ldots\ldots, \frac{\partial \mathrm{P}_{ij}}{\partial \delta_n} \frac{\partial \mathrm{P}_{ij}}{\partial V_{g+1}}, \ldots\ldots \frac{\partial \mathrm{P}_{ij}}{\partial V_n} \end{bmatrix}$ is line power flow sensitivity corresponding to angle and voltage magnitude.

For a single transaction case between seller bus m and buyer bus n, the change in power transactions can be substituted at position of bus m and bus n as:

$$\Delta \mathrm{P}_m = +\mathrm{P}_t$$
$$\Delta \mathrm{P}_n = -\mathrm{P}_t$$

$$\Delta P_{ij} = \left[\frac{\partial P_{ij}}{\partial \delta_2}, \ldots\ldots, \frac{\partial P_{ij}}{\partial \delta_n} \frac{\partial P_{ij}}{\partial V_{g+1}}, \ldots\ldots \frac{\partial P_{ij}}{\partial V_n}\right] [\mathbf{J}]^{-1} \begin{bmatrix} 0 \\ \vdots \\ +P_t \\ 0 \\ \vdots \\ -P_t \\ 0 \end{bmatrix} = ACPTDF_t * P_t \tag{14}$$

So, ACPTDFs for the transaction between seller bus m to buyer bus n can be represented as:

$$ACPTDF_{ij,mn} = \left[\frac{\partial P_{ij}}{\partial \delta_2}, \ldots\ldots, \frac{\partial P_{ij}}{\partial \delta_n} \frac{\partial P_{ij}}{\partial V_{g+1}}, \ldots\ldots \frac{\partial P_{ij}}{\partial V_n}\right] [\mathbf{J}]^{-1} \begin{bmatrix} 0 \\ \vdots \\ +1 \\ 0 \\ \vdots \\ -1 \\ 0 \end{bmatrix} \tag{15}$$

ACPTDFs are obtained for each line for particular transaction between seller and buyer bus. Now considering the different ways to determine Jacobian matrix and line flow sensitivities, ACPTDFs can be evaluated.
In the present work, three different methods have been considered for ACPTDFs determination and are categorized as:
1. N-R Jacobian based approach ($J_{N\text{-}R}$)
2. Reduced Jacobian based approach (J_{red})
3. Decoupled Newton Raphson based approach (J_{dec})

(A) N-R Jacobian based Approach

This approach is discussed in the previous section and ACPTDFs can be obtained using line flow sensitivity matrix and N-R Jacobian matrix. The power flow change can be expressed corresponding to line flow sensitivities with angle and voltage and change in angle and voltages can be obtained from N-R approach as:

$$\Delta P_{ij} = \left[\frac{\partial P_{ij}}{\partial \delta_2}, \ldots\ldots, \frac{\partial P_{ij}}{\partial \delta_n} \frac{\partial P_{ij}}{\partial V_{g+1}}, \ldots\ldots \frac{\partial P_{ij}}{\partial V_n}\right] [\mathbf{J}_{\mathbf{N-R}}]^{-1} \begin{bmatrix} 0 \\ \vdots \\ +\Delta P_t \\ 0 \\ \vdots \\ -\Delta P_t \\ 0 \end{bmatrix} = ACPTDF_t * P_t \tag{16}$$

$$ACPTDF_{ij,mn} = \left[\frac{\partial P_{ij}}{\partial \delta_2}, \ldots\ldots, \frac{\partial P_{ij}}{\partial \delta_n} \frac{\partial P_{ij}}{\partial V_{g+1}}, \ldots\ldots \frac{\partial P_{ij}}{\partial V_n}\right] [\mathbf{J}_{\mathbf{N-R}}]^{-1} \begin{bmatrix} 0 \\ \vdots \\ +1 \\ 0 \\ \vdots \\ -1 \\ 0 \end{bmatrix} \tag{17}$$

Both Jacobian and line flow sensitivity factors are taken without considering any assumptions.

(B) Reduced Jacobian based approach

In this method there are some modifications made in Jacobian calculation and line flow sensitivity factors. The assumptions taken are:

1. Change in the reactive power injection on buses is zero $(\Delta Q_i = 0)$.
2. Change in real power flow with respect to voltage is negligible. $(\frac{\partial P_{ij}}{\partial |V_i|} = 0)$

The new relationship between changes in power injection to angle can be expressed as:

$$\Delta P_i = J_1 \Delta \delta_i + J_2 \Delta |V_i| \tag{18}$$

$$0 = J_3 \Delta\delta_i + J_4 \Delta|V_i| \tag{19}$$

Put the value of $\Delta|V_i|$ in equation (using rules matrix multiplication)

$$\Delta P_i = [J_1 - J_2 J_4^{-1} J_3]\Delta\delta_i = [J_{red}]\Delta\delta_i \tag{20}$$

J_{red} is called reduced Jacobian matrix.

Hence, ACPTDFs for any transaction between seller bus m and buyer bus n can be written as:

$$ACPTDF_{ij,mn} = \left[\frac{\partial P_{ij}}{\partial \delta_2}, \ldots\ldots, \frac{\partial P_{ij}}{\partial \delta_n}\right] \left[\mathbf{J}_{\mathbf{red}}\right]^{-1} \begin{bmatrix} 0 \\ \vdots \\ +1 \\ 0 \\ \vdots \\ -1 \\ 0 \end{bmatrix} \tag{21}$$

(C) Decoupled Newton-Raphson based approach

In a decoupled N-R method, with assumptions of negligible variation of real power flow with voltage and negligible reactive power variation with angle, the partial Jacobian matrix J_2 and J_3 can be neglected.
So, ACPTDFs for the transaction seller bus m to buyer bus n can be written as

$$ACPTDF_{ij,mn} = \left[\frac{\partial P_{ij}}{\partial \delta_2}, \ldots\ldots, \frac{\partial P_{ij}}{\partial \delta_n}\right] \left[\mathbf{J_1}\right]^{-1} \begin{bmatrix} 0 \\ \vdots \\ +1 \\ 0 \\ \vdots \\ -1 \\ 0 \end{bmatrix} \tag{22}$$

The ACPTDFs thus obtained with three different approaches can be utilized for ATC computation.

(D) ATC determination for Simultaneous/multi-lateral transactions

In a deregulated market environment number of transactions can occur simultaneously as more and more participants are involved in the trading of power. When ATC is determined for more than one transactions occurring simultaneously in a system, ATC in such a case is called as simultaneous or multi-transaction ATC. The procedure for simultaneous ATC is similar as discussed for single transactions case with a change in the power injection matrix. In the simultaneous ATC case, the power injection matrix can be modified based on the transactions occurring between many sellers and buyers as:

$$\Delta \mathbf{P} = \begin{bmatrix} 0 \\ +P_t \\ \vdots \\ -P_t \\ 0 \\ +P_t \\ \vdots \\ -P_t \\ 0 \end{bmatrix} \tag{23}$$

Depending on the number of transactions, the entry at the corresponding seller and buyer buses can be added in the power transaction column matrix. Once this is known, the change in flows can be determined as obtained. The ACPTDFs with simultaneous transactions can be calculated as:

$$ACPTDF_{ij,mn} = \left[\frac{\partial \mathrm{P}_{ij}}{\partial \delta_2}, \ldots\ldots, \frac{\partial \mathrm{P}_{ij}}{\partial \delta_n} \right] [\mathbf{J}]^{-1} \begin{bmatrix} 0 \\ +1 \\ \vdots \\ -1 \\ 0 \\ +1 \\ \vdots \\ -1 \\ 0 \end{bmatrix} \tag{24}$$

The ACPTDs can be determined for simultaneous transaction case considering all the above discussed methods.

3. Line Outage Distribution Factors

The pre-outage state of a part of an interconnected power system network, where a line-*l* connected between bus-*r* and bus-*s* is shown in Fig. 1. Figure 2 shows the post outage state of the power system network with a line-*l* to be considered as out of service. The simulation of a line outage will require modification of [Y_{Bus}] parameters to exclude the parameters of the line-*l*, which changes the Jacobian matrix. This involves a time intensive process. A line outage has been approximately simulated by considering two fictitious generators at bus-*r* and bus-*s* and a fictitious line between the buses having the same parameters as the original line to retain the original [Y_{Bus}] and also the elements of Jacobian and power flow sensitivity matrix, [28]. Thus, retaining a fictitious line with the same parameters as that of an original line [Y_{Bus}] remains unaffected. The power flow in this fictitious line is considered as the pre-outage power flow in the actual line.

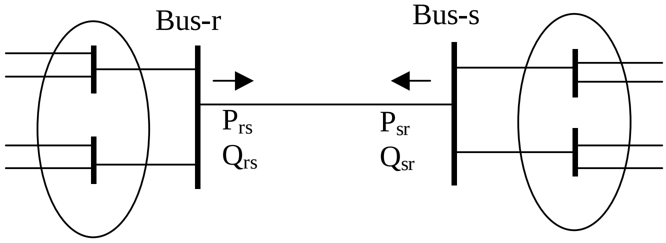

Fig 1 Pre-outage State of the Power System

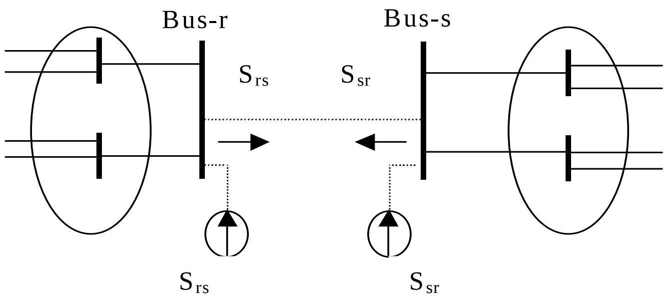

Fig 2 Post-outage State of the Power System

The power injected due to the fictitious sources has been taken same as the line flows at the two ends in order to make the net power flow to be zero thus, simulating the line outage condition. The changes in the bus power from pre-outage to post outage state at bus-*r* and bus-*s* for outage of the line-*l* are represented as:

$$\Delta P_r = P_{rs}^0, \Delta P_s = P_{sr}^0 \tag{25}$$

$$\Delta \mathrm{Q}_\mathrm{r} = Q_{rs}^0, \Delta Q_s = Q_{sr}^0 \tag{26}$$

Considering (25) and (26) as elements in the power injection mismatch vector, the change in angles as well as voltage magnitude can be computed using (6). Knowing these changes, new angle and voltage magnitude can be computed to determine the line flows and thus the change in the line flows. Knowing the change in line flows, LODFs can be defined. Now with help of PTDFs and LODFs, ATC can be evaluated for any outaged lines *r-s*.

4. ATC Determination for Intact System

ATC can be determined using all the three methods explained in previous sections. Methodology remains same for calculation of ATC. Three methods provide different Jacobian and line flow sensitivity factors which are used for calculation of ACPTDFs. Real power flows in base case obtained from N-R approach and line limits as a given data are utilized for ATC determination.

Now $P_{ij-mn}^{\max}$ for any transaction seller bus m to buyer bus n can be obtained as:

$$P_{ij-mn}^{\max} = \begin{cases} \dfrac{Limit_{ij}^{\max} - P_{ij}}{ACPTDF_{ij,mn}} & ; \quad ACPTDF_{ij,mn} > 0 \\ \infty \ (infinite) & ; \quad ACPTDF_{ij,mn} = 0 \\ \dfrac{-Limit_{ij}^{\max} - P_{ij}}{ACPTDF_{ij,mm}} & ; \quad ACPTDF_{ij,mn} < 0 \end{cases} \tag{27}$$

Where P_{ij} is the real power flow through any line *i-j*.

$Limit_{ij}^{\max}$ is thermal limit of any line *i-j*.

$P_{ij,mn}^{\max}$ is the maximum allowable transaction (bilateral, simultaneous/multi-lateral transaction) amount from bus/zone *m* to bus/zone *n* constrained by the line flow limit from bus/zone *i* to bus/zone *j*. For the given transaction, the ATC can be defined and obtained as:

$$ATC_{mn} = \min\left\{P_{ij,mn}^{\max} \quad ij \in N_l\right\} \tag{28}$$

where, N_l is the total number of lines in the system.

ATC Determination with Line Contingency

According to ATC principles, reasonable level of uncertainties should be accommodated in ATC calculations [1]. Line outage as contingency cases should be considered for ATC calculations as it is limited by the effect of contingencies. ACLODFs and ACPTDFs can be combined together to calculate available transfer capability. This is the maximum increase in the transaction amount from a bus/zone to another bus/zone under (n-1) contingency condition. Consider a transaction from zone *m* to zone *n* and the outage of the line from bus/zone *r* to bus/zone *s* (line-*rs*). The change in the flow on the line-*rs* due to the given transaction is:

$$\Delta P_{rs}^{new} = ACPTDF_{rs,mn} * P_{mn}^{new} \quad (29)$$

When the outage of line-*rs* is considered, the part of the flow appears on any line *ij*. Thus, the change in flow in the line *ij* resulting from outage of the line-*rs* along with a new transaction from bus/zone *m* to bus/zone *n* is given by:

$$\Delta P_{ij,rs}^{new} = \left(ACPTDF_{ij,mn} + ACLODF_{ij,rs} * ACPTDF_{rs,mn}\right) * P_{mn}^{new} \quad (30)$$

The ATC from bus/zone *m* to bus/zone *n*, with outage of line *rs* is given as [21]:

$$ATC_{mn,rs} = \min\left\{ \frac{P_{ij}^{\max} - P_{ij}^{0}}{ACPTDF_{ij,mn} + ACLODF_{ij,rs} * ACPTDF_{rs.mn}} \quad ij \in N_l \right\} \quad (31)$$

All possible combinations of lines outages and limiting lines should be checked. Then, ATC can be evaluated as:

$$ATC_{mn,rs} = \min(ATC_{mn}, ATC_{mn,rs}) \quad (32)$$

The steps for calculation of ATC can be summarized in the flow chart shown in Fig. 3.

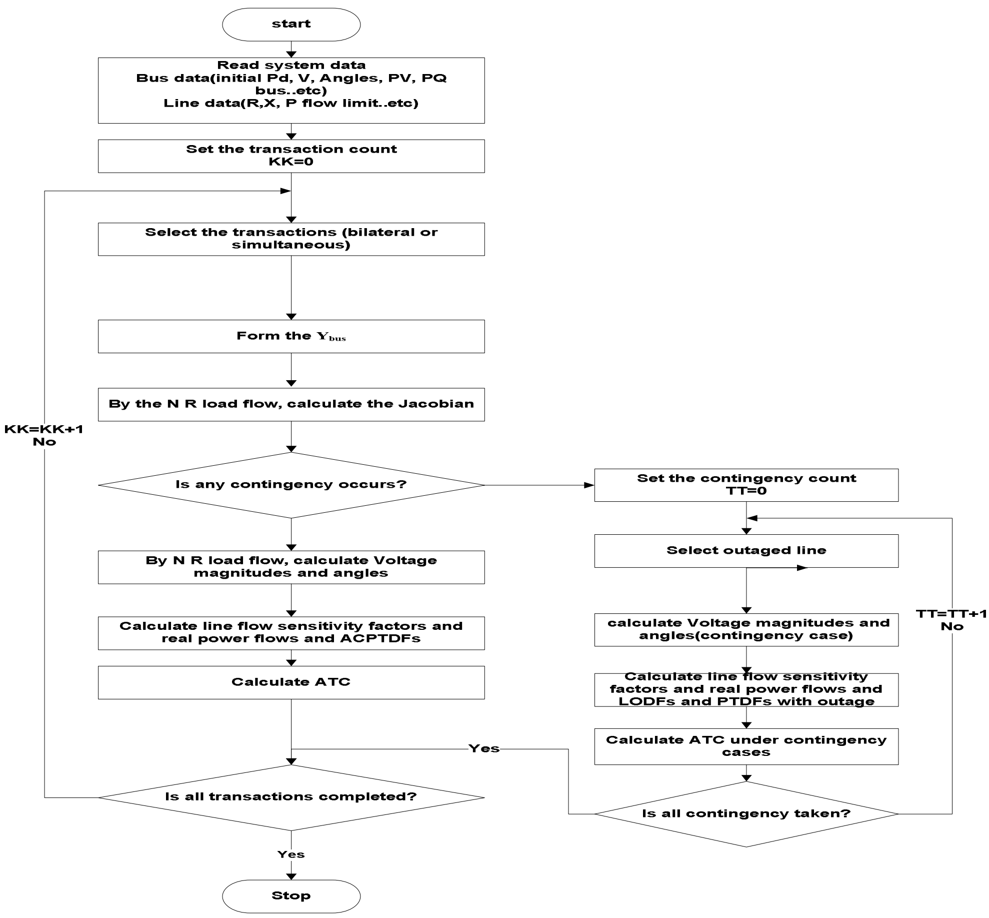

Fig.3. Flow chart for ATC determination

5. Results and Discussions

Available transfer capability has been obtained for different transactions taken as single and simultaneous/multi-transactions for intact as wells as with line contingencies for IEEE 24 bus RTS. 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: transaction between seller buses 23 and 10 to buyer bus 15 bus 3(simultaneous transactions)
T4: transaction between seller buses 23, 10, 21 to 15, 3, 6 (multi-transactions)

ACPTDFs computed for three methods for transactions T1 to T3 are shown in Figs. 4 to 6. It is observed that the ACPTDFs are different for different transactions. This is due to the change in power flow sensitivity and Jacobian elements based on the transactions. Some lines have very high values of PTDFs as observed in figures 4 to 6. The results of ATC determination with the three methods have been obtained based on the method discussed in the section of methodlogy and the algorithmic steps provided in Fig. 3.

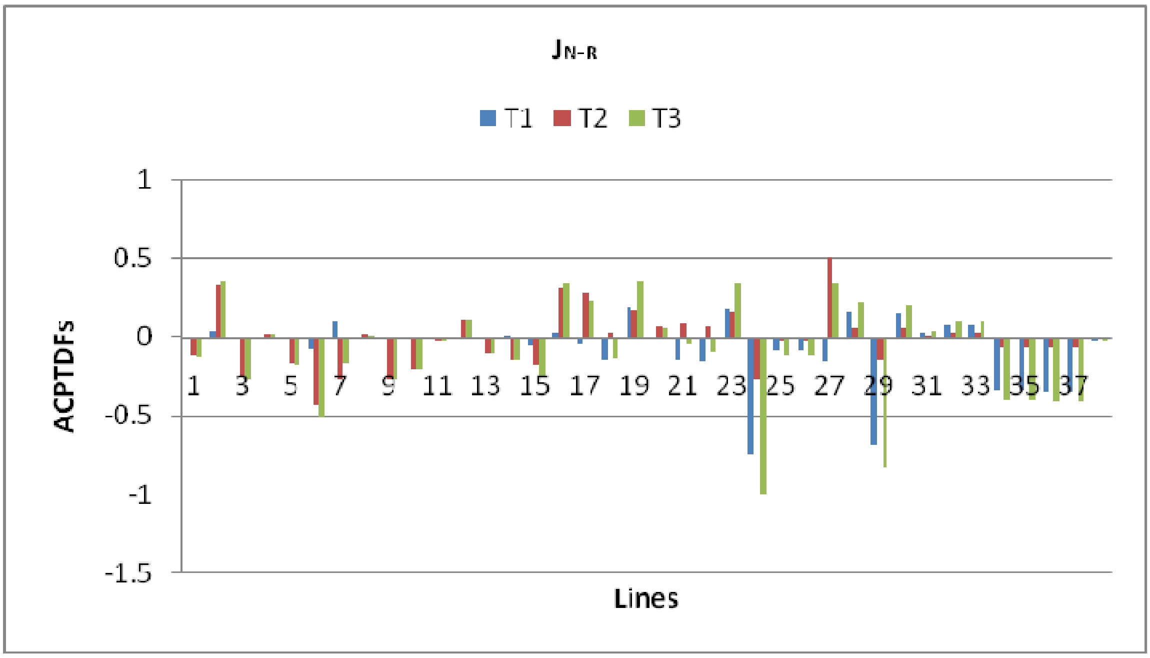

Fig 4. ACPTDFs with N-R Jacobian based approach

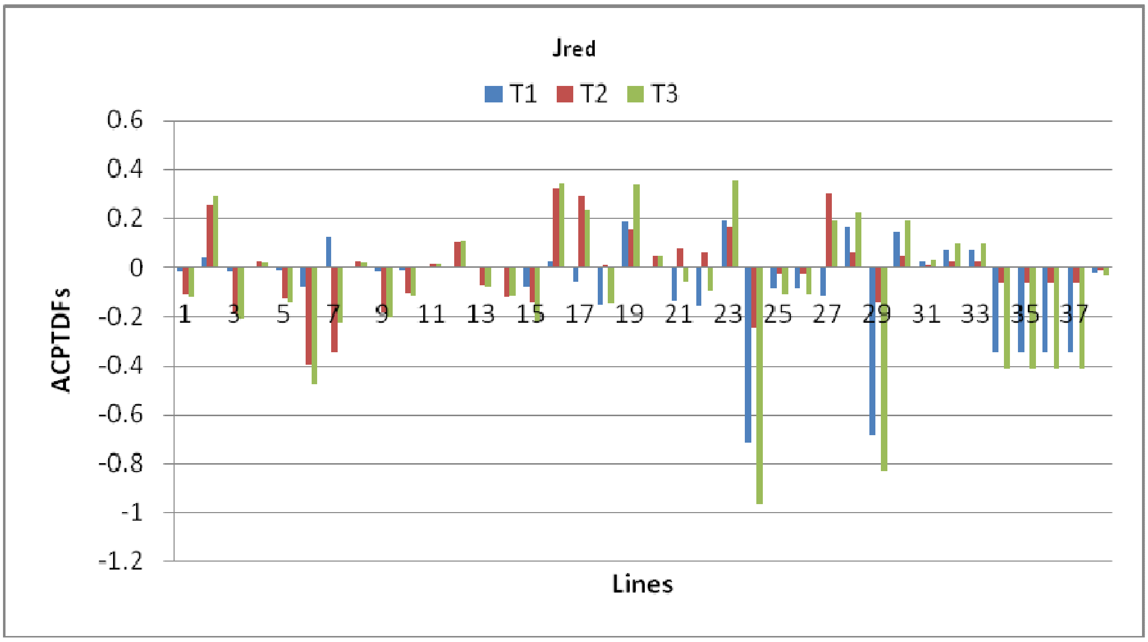

Fig. 5. ACPTDFs with reduced Jacobian based approach

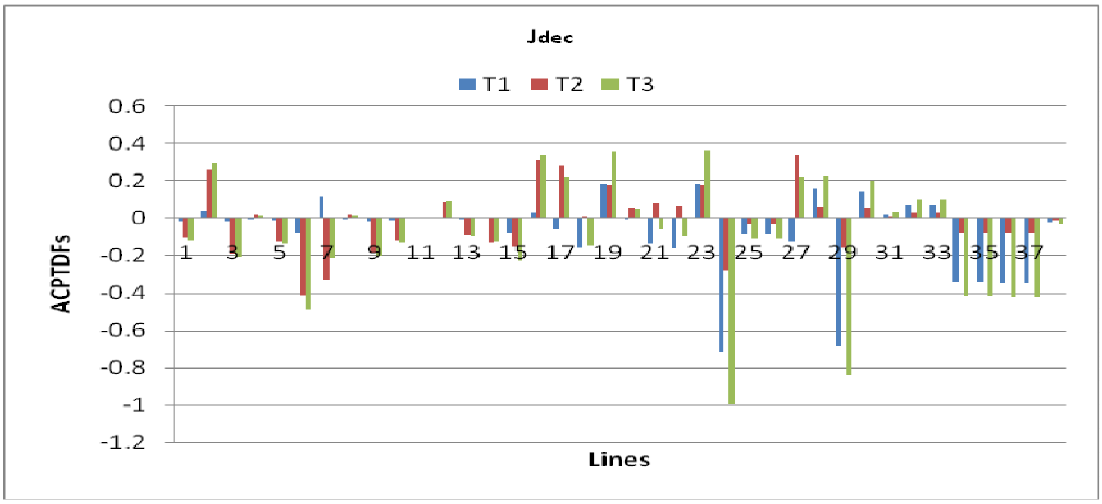

Fig.6.Decoupled N-R based approach

The ATCs are determined for different transactions using three AC load flow based approaches. The ATC values for all transactions are given in Table 1. The ATC values are also shown in Fig. 7. It is observed from Table as well as from Fig. 7, ATC is observed to be lower for simultaneous/multi-transactions cases.

Table 1. ATC (p.u) with different AC methods

Transactions	ATC(p.u)		
	J_{N-R}	J_{red}	J_{dec}
T1	7.5785	7.8219	7.8306
T2	2.8342	4.0997	3.401
T3	2.7629	3.8432	3.2432
T4	1.1183	1.1362	1.09769

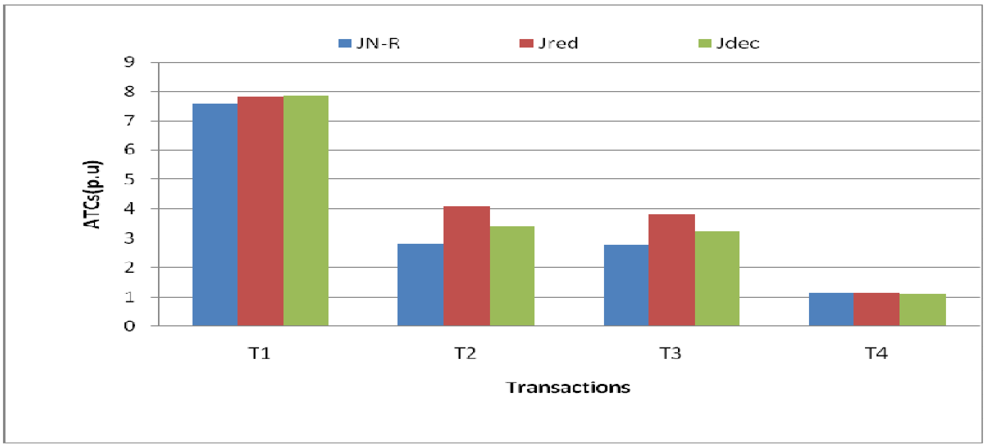

Fig. 7. ATCs (p.u) for different AC methods

ATCs for transactions T1, T2, and T3 with N-R Jacobian based approach are found to be lower compared to reduced Jacobian and decoupled Jacobian based approach, however, for transaction T4, the values of ATC is found higher than decoupled Jacobian based method. The method based on J_{N-R} is more accurate than others as in this case there are no assumptions involved. ATC for transactions T1, T2, T3 and T4 are found in close agreement with other methods. ATC values for transaction T4 are observed lower most compared to all other transactions. The comparison of ATCs obtained with DC method and all AC methods are given in Table 2. It is observed that ATC obtained with three different approaches for PTDFs calculations are different and closely matching their results for all transactions cases. It is observed from Table that ATC values obtained with Jred approach are in close agreement with DC method. Since DC method is based on assumptions, the values may not give accurate information to the ISO for better market operation.

Table 2. Comparison of ATCs

Transactions	ATC(p.u)			
	DC method	J_{N-R}	J_{red}	J_{dec}
T1	7.8362	7.5785	7.8219	7.8306
T2	3.6876	2.8342	4.0997	3.4010
T3	3.5024	2.7629	3.8432	3.2432
T4	0.9211	1.1183	1.1362	1.0977

ATC under Line Contingency case

The ATCs have been determined for contingency cases considering few line outages. The lines taken for study are: 9-12, 16-19, 19-20, and 20-23. The ATC determined with all the methods are calculated and are given in Table 3 to Table 5. The ATC values obtained with different methods are also shown in Figs 8 to 10. It is observed from the Figs. that ATC values are higher for single transaction case T1 and T2 and for multi-transactions case, ATC is found lower. ATC is found minimum for transaction T3 with line outage 9-12. For simultaneous transaction T1, ATC is observed higher for outage of line 19-20 and 16-19 compared to other line outage cases.

The ATC obtained with line contingencies for all transactions with three approaches to calculate PTDFs are presented in Table 3 to Table 5. Comparing ATCs obtained with all methods, it is observed that the values are different for all transaction cases and are also in close agreements. However, for the line outage 9-12, ATC is found to be lower for all methods for transactions T2 to T4. For transaction T3 and T4, ATCs are found lower for all line outages as compared to the case with other transactions. For transaction T1, ATC is found minimum for line outage 20-23. For tansaction T4, ATC values are found minimum for all line outages compared to all other tranactions except for line 9-12. Similar observations are found for other methods of ATC calculations. For multitransactions cases, ATC values are lower compared to single transaction cases. The results obtained with DC method are also presented in Table 5I for line contingencies for comparison. It is observed after comparing ATCs obtained with DC and all AC methods for line contingencies, for transactions T3 and T4 the values are lower as compared to other transaction cases. Hence for multi-transactions ATCs are found lower for both intact as well as line contingency cases as also observed from Figs. 8 to 10. This is due to the fact that power flow increases in all lines following more transactions and thereby reducing ATC for a system.

Table 3. ATCs (p.u) using J_{N-R} with line outage case

Outaged line	ATC(p.u) J_{N-R}			
	T1	T2	T3	T4
9-12	5.2978	0.4683	0.4303	0.5626
16-19	6.3310	2.8714	2.7236	1.1203
19-20	6.4196	2.8199	2.7236	1.1167
20-23	4.0590	2.8180	2.7236	1.1175

Table 4. ATCs (p.u) using Jred with line outage case

Outaged line	ATC(p.u) J_{red}			
	T1	T2	T3	T4
9-12	5.9340	0.5980	0.5197	0.5665
16-19	6.2900	4.1200	3.5408	1.1336
19-20	6.3200	4.0710	3.7671	1.1325
20-23	4.0910	4.0700	3.4087	1.1338

Table 5. ATCs (p.u) using J_{dec} with line outage case

Outaged line	ATC(p.u) J_{dec}			
	T1	T2	T3	T4
9-12	5.9340	0.5990	0.4410	0.8500
16-19	6.2900	4.1200	3.0568	1.0978
19-20	6.3200	4.0700	3.2026	1.0965
20-23	4.0900	4.0690	3.2103	1.0977

Table 6. ATCs (p.u) using DC method with line outage case

Outaged line	ATC(p.u) DC method			
	T1	T2	T3	T4
9-12	6.63	1.03	0.91	0.76
16-19	6.49	3.64	3.27	0.93
19-20	5.22	3.68	3.46	0.92
20-23	4.09	3.68	3.39	0.92

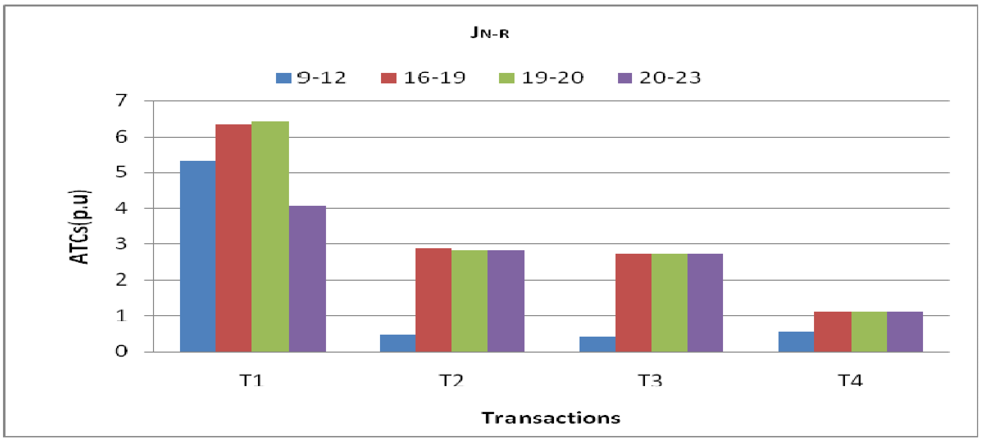

Fig. 8. ATCs (p.u) by N-R Jacobian based method

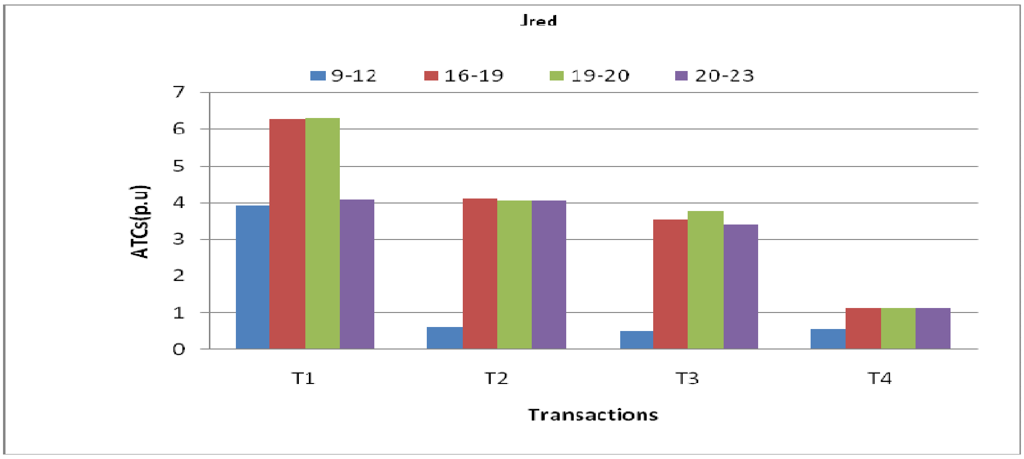

Fig. 9. ATCs reduced Jacobian based approach

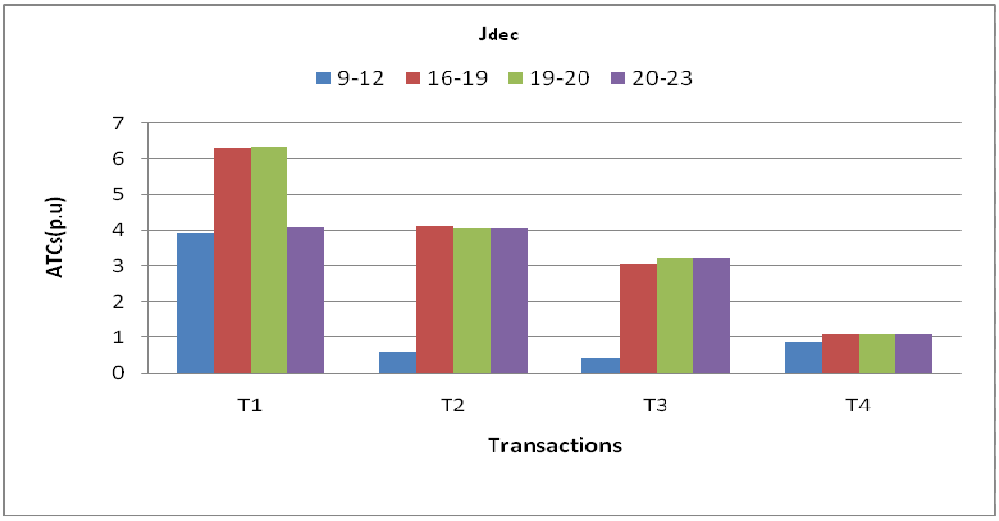

Fig.10. ATCs reduced Jacobian based approach

6. Conclusions

In this paper, methodology for ATC determination has been proposed for simultaneous/ multi-transactions in deregulated electricity market based on AC power transfer distribution factors. Three methods based on Jacobian and power flow sensitivity calculations have been implemented for simultaneous/ multi-transactions cases for ATC determination under intact and line outage cases. The ATC with simultaneous transaction case as well as in multi-transaction case are found lower compared to the other transactions. In line contingency cases, ATC is found to decrease for all transactions compared to intact case. ATC reduces for multi-transaction cases with intact and contingency cases. The results obtained with AC PTDF based method is more accurate compared to DC PTDF based approach as there are no assumptions involved with N-R based ACPTDF approach. The method with AC approach can be implemented online ATC calculations.

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