Dynamic Available Transfer Capability
Evaluation Considering Hopf Bifurcation Limit

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Abstract—This paper has suggested an optimization based method to evaluate dynamic Available Transfer Capability (ATC) considering Hopf bifurcation limit, in an electricity market having bilateral as well as multilateral transactions. The effect of line contingencies has also been considered in the ATC determination. The critical contingencies have been identified by utilizing an oscillatory stability based contingency screening index, taking into account the impact of transactions on the relative severity of the contingencies. The effectiveness of the proposed method has been demonstrated on 39-bus New England system considering composite static load as well as dynamic load models.

I. INTRODUCTION

In a restructured electricity market, the market participants share a common transmission network for wheeling power from the point of generation to the point of consumption. All the participants, in the open access environment, may try to maximize their profit and procure the electrical energy from the cheapest source, which may, sometimes lead to congestion of certain transmission corridors, thereby, undermining the system security and reliability. Therefore, the Available Transfer Capability (ATC) of the transmission system needs to be determined at regular intervals to ensure that the system security is maintained while serving a wide range of transactions.

The ATC of a transmission network refers to its unutilized transfer capability available for further transactions, over and above already committed usage, without violating system security constraints [1]. The constraints required to determine ATC include static constraints such as line thermal limits, voltage limits and maximum loadability limits as well as stability constraints. ATC, determined using the static constraints, has been termed as static ATC and that, determined using both static and dynamic constraints, is termed as dynamic ATC.

Various approaches have been proposed in the literature to determine static ATC such as continuation power flow [2], ac power flow [3], dc power flow [4], optimal power flow [5], and sensitivity [6] based methods. However, fast evaluation of dynamic ATC, considering stability constraints is still a challenging task. Ref. [7] has focused on loss of stability associated with phase angle behavior and electromechanical swing modes as an important constraint on ATC. An iterative approach, utilizing trajectory sensitivity concept, has been proposed in [8] for computing dynamic ATC. A static optimization based approach, including dynamic security constraints for the assessment of ATC, has been proposed in [9]. An integrated scheme, based on coupling of an OPF program with a transient stability constrained Maximum Allowable Transfer (MAT) program, was proposed for ATC determination including static and transient stability constraints in [10]. Dynamic ATC computation has been formulated as an optimization problem in [11] with positive energy margin as an additional constraint along with other static constraints. A model, using equilibrium equations as steady state constraints and dot product concept given in [9] as rotor angle stability constraint, has been proposed in [12] to determine dynamic ATC. In [13], estimation of Point of Maximum Potential (POMP) and Potential Energy Boundary Surface (PEBS) has been proposed, instead of computing it iteratively, to determine dynamic ATC considering classical model of generators.

Though various efforts have been made to incorporate transient stability constraints into optimization formulation to determine dynamic ATC, few methodologies are available to compute ATC constrained by oscillatory instability, which is often related to Hopf bifurcation. Since the transmission systems operate under stressed conditions due to the increased transactions, oscillatory stability limit is equally important in determining the ATC. Ref. [14] proposed an optimization formulation, with an objective to minimize the real part of the critical eigen values subject to the Hopf bifurcation and power balance constraints, to obtain the dynamic ATC. However, to obtain the static ATC, this requires a different formulation. Further, the effect of contingencies on the ATC calculation has not been considered.

In this paper, a new optimization based formulation has been suggested to determine dynamic ATC in an electricity market, having bilateral as well as multilateral transactions. Hopf bifurcation constraints have been included in the optimization model. An oscillatory stability based contingency screening index, which takes into account the impact of transactions on relative severity of contingencies, has been used to reduce the list of credible contingencies to be considered in determining the ATC. The proposed method has been applied for dynamic ATC determination on 39-bus New England system having composite static load model as well as dynamic induction motor load models. The results obtained...
with the proposed formulation have also been compared with those obtained using the formulation proposed in [14].

II. MODELING OF POWER SYSTEM COMPONENTS

In this work, the synchronous generators have been represented by two-axis flux decay dynamic model along with IEEE type-1 DC exciter [15]. The real power loads have been represented as composite ZIP (‘Z’ represents constant impedance, ‘I’ represents constant current and ‘P’ represents constant power components) load model. However, the reactive power loads have been represented as composite ZIP (‘Z’ represents constant power components) load model. However, the real power loads have been represented as constant impedance type as recommended in [20] by IEEE Task Force. Composite model of the real power loads, in terms of the load bus voltage \( V \), is expressed as follows,

\[
P = P_0 \left[ a_0 + a_1 \left( \frac{V}{V_0} \right) + a_2 \left( \frac{V}{V_0} \right)^2 \right]
\]

(1)

where, \( a_0, a_1, a_2 \) are the per unit load coefficients, such that \( a_0 + a_1 + a_2 = 1 \). \( P_0 \) is the real power load at nominal voltage \( V_0 \). For constant impedance type load, \( a_0, a_1 \) are zero and \( a_2 = 1 \). The modeling of the induction motor is described below.

A. Dynamic Model of Induction Motor Loads

A third order induction motor model [16], neglecting stator transients, has been used for dynamic load modeling. Equations describing the model, at a load bus-\( i \), are given as,

\[
T_{m_i} E_{qmi} = -E_{qmi} + (X_i' - X_i) I_{dmi} + E_{dmi} S_{mi} T_{m_i}
\]

(2)

\[
T_{m_i} E_{dmi} = -E_{dmi} - (X_i' - X_i) I_{qmi} - E_{qmi} S_{mi} T_{m_i}
\]

(3)

\[
S_{mi} = \frac{1}{2H_{mi}} \left( T_{m_i} - T_{ei} \right)
\]

(4)

where,

\[
S_{mi} = \left( \omega_{mi} - \omega_s \right)
\]

\[
T_{m_i}\text{ is the transient open circuit time constant, } \frac{\omega_{mi}}{\omega_s}\text{ is the rotor speed, } E_{dmi}, E_{qmi}\text{ are the transient direct and quadrature axis induced voltages, } I_{dmi}, I_{qmi}\text{ are the direct and quadrature axis stator currents, } X_i', X_i\text{ are the steady state and transient reactances, } H_{mi}\text{ is the inertia constant of the induction motor.}
\]

III. MODELING OF BILATERAL/MULTILATERAL CONTRACTS

The conceptual model of a bilateral contract in a competitive electricity market is such that sellers and buyers enter into transactions, where the quantities traded and the associated prices are at the discretion of these parties and do not involve System Operators (SOs). If there is no security violation, the SO dispatches all requested transactions and charges for the transmission service. Mathematically, each bilateral transaction, between a seller at bus-p and power purchaser at bus-q, satisfies the following power balance relationship.

\[
P_{gp} - P_{dq} = 0
\]

(5)

where, \( P_{gp} \) and \( P_{dq} \) are the real power generation at bus-p and real power consumption at bus-q. The bilateral concept can be generalized to the multilateral case, where the seller (for example a generation company) may inject power at several nodes and the buyers also draw load at several nodes. A transaction power balance, ensuring the aggregate injection equal to the aggregate draw-off for each transaction, must be satisfied. The contracted demands of buyers to be provided by generators must be shared in a proportion decided by the contracted parties. Mathematically, a multilateral contract-\( k \), involving more than one supplier and/or consumer, can be expressed as,

\[
\sum_{m} P_{gm}^k - \sum_{n} P_{dn}^k = 0, k = 1, 2, \ldots t_k
\]

(6)

where, \( P_{gm} \) and \( P_{dn} \) stand for the power injections into the seller bus-\( m \) and the power taken out at the buyer bus-\( n \), respectively, and \( t_k \) is the total number of the multilateral contracts.

IV. PROBLEM DEFINITION

A. Available Transfer Capability (ATC)

According to a NERC report [1], ATC is defined as:

\[
\text{ATC} = \text{TTC} - \text{TRM} - \{\text{ETC} + \text{CBM}\}
\]

In general, the ATC (without considering system margins) is defined as TTC (total transfer capability) less ETC (existing transmission commitments). Various operating margins, such as Transmission Reserve Margin (TRM) and Capacity Benefit Margin (CBM) are to be accounted for separately, when such a definition is used for ATC determination, thus showing the direct relationship between ATC and TTC. Hence, all the constraints applicable to determination of the TTC are also applicable to the determination of the ATC.

B. Hopf Bifurcation and Oscillatory Stability

The behavior of a power system can be described by a set of Differential-Algebraic Equation (DAE) written, in a general form, as,

\[
x = F(x, y, p)
\]

\[
y = G(x, y, p)
\]

(7)

(8)

where, \( x \) is a vector of dynamic variables, \( y \) is a vector of algebraic variables and \( p \) is a vector of parameters. In this work, load parameter \( \lambda \) has been varied at seller and buyer buses to obtain Hopf bifurcation point. The new generation and load demand with this parameter are represented as,

\[
P_{gi} = P_{gi}^0 * \lambda
\]

\[
P_{di} = P_{di}^0 * \lambda
\]

(9)

(10)

where, \( P_{gi}^0, Q_{gi}^0 \) are the base case generation and load at any bus-\( i \). Equation (7) represents the dynamic equations of generators, loads and excitors, whereas (8) represents the power flow equations at generator and load buses. Equations (7) and (8) can be linearised around an initial operating point \( (x^*, y^*) \) and can be written in the form of
The eigenvalues of the reduced Jacobian matrix, \( A_{\text{red}} \), undergo changes for any variation in the parameters \( p \). One pair of the complex eigenvalues of the reduced system Jacobian matrix may reach the imaginary axis resulting in Hopf bifurcation. This may cause oscillatory instability leading to voltage collapse. When the bifurcation parameter \( p \) is further changed, the complex pair of eigenvalues may move away from the imaginary axis, either to the right or to the left of the imaginary axis. Consequently, stable or unstable limit cycles (oscillations) may appear or disappear.

At Hopf bifurcation, one pair of the complex eigenvalues become purely imaginary, say \( \pm \mu^* \), and the damping ratio becomes zero. The associated eigenvector \( \mathbf{v} \) becomes a complex vector, say \( (\mathbf{v}^*)^T + j(\mathbf{v}^*)^T \). Substituting this into (14) and separating real and imaginary parts, provides

\[
\begin{align*}
\mathbf{A}_{\text{red}} \mathbf{v}^* &= -\mu^* \mathbf{v}^* \\
\mathbf{A}_{\text{red}} \mathbf{v}^1 &= \mu^* \mathbf{v}^1
\end{align*}
\]

### C. Contingency Screening Index

Contingency screening is an important step in the fast assessment of static as well as dynamic ATC. Accuracy of ATC determination depends on the accurate selection of the severe contingencies out of the contingency list. In an open power market, different transactions are likely to take place and the severity order of a contingency may not be the same for each transaction. The transfer capability is limited by a contingency, whose severity is largely affected by introduction of the transaction. Hence, it is necessary to quantify the severity of contingencies considering the influence of the transaction. For this purpose, the following index, based on the change in the damping ratio associated with the most critical complex eigenvalue (closest to the imaginary axis) at base case loading and with an additional transaction [17], has been used. An oscillatory stability-based contingency screening index \( SDR_k \) for a kth contingency has been defined as,

\[
SDR_k = \frac{\xi_{\text{cr,Bk}} - \xi_{\text{cr,Ti}}}{\xi_{\text{cr,Bk}}}
\]

where, \( \xi_{\text{cr,Bk}} \) and \( \xi_{\text{cr,Ti}} \) are the damping ratio associated with the most critical complex eigenvalue (closest to the imaginary axis) at the base case loading and for an additional transaction \( T_i \), respectively. The value of additional transaction \( T_i \) should be selected such that the decrease in damping ratio is significant. The index \( SDR_k \) becomes large, if the damping ratio decreases considerably by the introduction of the transaction. The contingencies with the larger values of \( SDR_k \) are considered in the list of severe contingencies.

### D. Proposed Formulation for ATC Determination

The dynamic ATC values have been determined as the change in loading from the base case conditions to that corresponding to a Hopf bifurcation point. The Hopf bifurcation point has been obtained by formulating it as an optimization problem with an objective to maximize the scalar loading parameter \( \lambda \). The proposed formulation of the optimization problem to determine the Hopf bifurcation limit in an electricity market, involving multilateral and bilateral contracts, is given below.

\[
\begin{align*}
\text{Max} \quad & \lambda \\
\text{s.t.} \quad & F(\mathbf{x}, \mathbf{y}, \lambda) = 0 \\
& G(\mathbf{x}, \mathbf{y}, \lambda) = 0 \\
& P_{Gm}^{k} - P_{Dm}^{k} = 0 \\
& \sum_{m} P_{Gm}^{k} - \sum_{n} P_{Dm}^{k} = 0 \quad k = 1, 2, ..., t_k \\
& \mathbf{A}_{\text{red}} \mathbf{v}^* = -\mu^* \mathbf{v}^1 \\
& \mathbf{A}_{\text{red}} \mathbf{v}^i = \mu^* \mathbf{v}^i \\
& \text{Minimum}(\xi_{\text{cr}}) \geq 0 \\
& ||\mathbf{v}^1|| = 0 \\
& ||\mathbf{v}^i|| = 0
\end{align*}
\]

The optimal value of \( \lambda \) has been obtained by solving the above optimization problem using sequential quadratic programming and the constraints (24) and (25) have been considered implicitly while solving this problem. This requires estimation of the initial values of the system state variables, which have been obtained as following [18].

(i) Run a load flow to solve equation (8) for a base case \( \lambda = 1 \) operating point. This provides initial values of load flow variables \( \mathbf{y} \).

(ii) Obtain the dynamic state variables \( \mathbf{x} \) by solving set of nonlinear equations described by equation (7) with \( \dot{\mathbf{x}} = 0 \).
(iii) Obtain the reduced Jacobian $A_{\text{red}}$, defined in equation (16), for the values of $x$ and $y$ computed in steps (i) and (ii).

(iv) After computing the eigen values of matrix $A_{\text{red}}$, determine the eigen value $\sigma$ having smallest real part and its imaginary part $\mu = \text{imag}(\sigma)$ and also determine the damping ratio associated with it.

(v) Calculate vectors $v^r$ and $v^i$ representing the real and imaginary parts of eigenvector corresponding to the eigen value $\sigma$, respectively.

(vi) To satisfy non-zero norm conditions of the real and imaginary parts of eigenvectors as in (27) and (28), the vectors $v^r$ and $v^i$ have been normalized by dividing each of them by their first element.

With these initial values of the state variables, the optimization problem given by (19)-(28) was solved, for a given transaction, to determine the critical value of $\lambda$ at Hopf bifurcation point. Here, $\lambda = 1$ corresponds to no transfer (base case) and $\lambda = \lambda_{\text{max}}$ corresponds to the maximum transfer. TTC and ATC for a transaction $i$, in each case (normal or contingency case), is calculated as following.

$$\text{TTC}_i = P_{Dh}^0 + \lambda_{\text{max}}, \ \forall i \in t_k$$  \hfill (29)

$$\text{ATC}_i = P_{Dh}^0 + \lambda_{\text{max}} - P_{Dh}^0, \ \forall i \in t_k$$  \hfill (30)

where, $t_k$ is the number of transactions.

E. Formulation for ATC Determination Given in [14]

A bifurcation based approach to determine ATC in the electricity markets was proposed in [14]. The Hopf bifurcation point was obtained using an optimization formulation, with an objective to minimize the real part $\alpha_{e_{\text{cri}}}$ of the critical eigenvalues while satisfying the Hopf bifurcation conditions. The formulation of the optimization problem to determine the Hopf bifurcation limit is given below.

$$\text{Min} \|\alpha_{e_{\text{cri}}}\|$$ \hfill (31)

s.t.

$$F(x,y,\lambda) = 0$$ \hfill (32)

$$G(x,y,\lambda) = 0$$ \hfill (33)

$$P_{Gr} - P_{Dh} = 0$$ \hfill (34)

$$\sum_{m}^{k} p_{Gm}^k - \sum_{n}^{k} p_{Dn}^k = 0 \ \ k = 1,2,\ldots,t_k$$ \hfill (35)

$$A_{\text{red}}v^r = -\mu_i\{v^i\}$$ \hfill (36)

$$A_{\text{red}}v^i = \mu_i\{v^r\}$$ \hfill (37)

$$\|v^r\| \neq 0$$ \hfill (38)

$$\|v^i\| \neq 0$$ \hfill (39)

V. SIMULATION RESULTS

The proposed approach for dynamic ATC determination has been applied on 39-bus, 10-generator, New England system [19], shown in Fig. 1. The details of different bilateral and multilateral transactions considered are shown in Table I. To demonstrate the effectiveness of the proposed formulation, only those transactions have been included for which Hopf bifurcation occurred. ATC has been determined for two different loading scenarios. One of the load scenario consider all the real power loads to be static ZIP type (composite load model) containing 60% constant power, 20% constant current and 20% constant impedance, whereas all the reactive power loads are assumed as constant impedance type. The second load scenario is same as the first scenario except that it assumes half of the load at buyer buses to be dynamic loads represented by induction machine model. For ATC determination, both the real and the reactive power loading at the selected buses have been increased. The real and the reactive power outputs of the generators, participating in the transactions have been increased by the amount of load change in the ratio decided by the bilateral/multilateral contracts. The slack bus generator is assumed to supply the change in the system loss.

Contingency screening was performed using (18) for different transactions, as mentioned in the part C of section IV. Table II shows the top five severe contingencies for the transactions T1, T3, T5 and T7 only, due to space constraint. However, top 10 severe contingencies were considered while determining the ATC. Second column shows the connecting buses of the lines which are taken out. The third and fourth columns show the value of the damping ratio associated with the most critical eigen value at the base case and for an additional transaction T, respectively. Fifth column shows the value of the contingency screening index $SDR_k$. The contingencies, with higher value of $SDR_k$, have been considered in the contingency list.

After identifying the severe contingencies, the ATC assessment was carried out for the base case and critical contingency cases using the proposed formulation for both the load scenarios considered. The ATC values for transaction T1 at the base case and the critical contingency cases, with the ZIP load and the dynamic load models, are shown in Tables III and IV, respectively. First column shows the end buses of lines.
where "0" indicates the base case condition. Second and third columns show the optimal value of \( \lambda \) at which Hopf bifurcation occurs and the corresponding ATC values, respectively. After obtaining the optimal value of \( \lambda \) by solving the optimization problem, the critical eigen values were obtained which are shown in column 4. These critical eigen values have zero real part, which demonstrate the accuracy of the proposed formulation. It can be observed that though the ranking order of the contingencies is not same as given in Table II, the critical contingencies are filtered out as demonstrated by the ATC values. The ATC values are much lower as compared to that at the base case. The most credible contingency as shown in Table II for transaction T1 does not correspond to the minimum ATC value in Table III due to different transaction values in the two cases.

**Table II: Contingency Ranking for Different Transactions**

<table>
<thead>
<tr>
<th>Transaction</th>
<th>Line Outage</th>
<th>( \delta_{cr, Bi} )</th>
<th>( \delta_{cr, Ti} )</th>
<th>SDR,</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>31-1</td>
<td>0.0362</td>
<td>-0.0622</td>
<td>2.7182</td>
</tr>
<tr>
<td></td>
<td>38-31</td>
<td>0.0364</td>
<td>-0.0599</td>
<td>2.6456</td>
</tr>
<tr>
<td></td>
<td>29-28</td>
<td>0.2949</td>
<td>-0.2718</td>
<td>1.9216</td>
</tr>
<tr>
<td></td>
<td>26-29</td>
<td>0.2911</td>
<td>-0.1765</td>
<td>1.6063</td>
</tr>
<tr>
<td></td>
<td>38-25</td>
<td>0.2679</td>
<td>-0.1514</td>
<td>1.5651</td>
</tr>
<tr>
<td>T3</td>
<td>38-25</td>
<td>0.2679</td>
<td>-0.1913</td>
<td>1.2702</td>
</tr>
<tr>
<td></td>
<td>29-28</td>
<td>0.2949</td>
<td>-0.1749</td>
<td>1.2048</td>
</tr>
<tr>
<td></td>
<td>31-1</td>
<td>0.0362</td>
<td>-0.0353</td>
<td>1.1104</td>
</tr>
<tr>
<td></td>
<td>38-31</td>
<td>0.0364</td>
<td>-0.0333</td>
<td>1.0659</td>
</tr>
<tr>
<td></td>
<td>26-29</td>
<td>0.2911</td>
<td>-0.0748</td>
<td>0.8498</td>
</tr>
<tr>
<td>T5</td>
<td>31-1</td>
<td>0.0362</td>
<td>-0.0217</td>
<td>1.5994</td>
</tr>
<tr>
<td></td>
<td>38-31</td>
<td>0.0364</td>
<td>-0.0198</td>
<td>1.5439</td>
</tr>
<tr>
<td></td>
<td>38-25</td>
<td>0.2679</td>
<td>-0.1245</td>
<td>1.4647</td>
</tr>
<tr>
<td></td>
<td>29-28</td>
<td>0.2949</td>
<td>-0.1084</td>
<td>1.3675</td>
</tr>
<tr>
<td></td>
<td>26-29</td>
<td>0.2911</td>
<td>-0.0035</td>
<td>1.0120</td>
</tr>
<tr>
<td>T7</td>
<td>29-28</td>
<td>0.2949</td>
<td>-0.0725</td>
<td>1.2458</td>
</tr>
<tr>
<td></td>
<td>38-25</td>
<td>0.2679</td>
<td>-0.0464</td>
<td>1.1731</td>
</tr>
<tr>
<td></td>
<td>26-29</td>
<td>0.2911</td>
<td>0.0309</td>
<td>0.8938</td>
</tr>
<tr>
<td></td>
<td>21-22</td>
<td>0.2945</td>
<td>0.0313</td>
<td>0.8937</td>
</tr>
<tr>
<td></td>
<td>38-37</td>
<td>0.3007</td>
<td>0.0351</td>
<td>0.8832</td>
</tr>
</tbody>
</table>

**Fig. 2** compares the ATC values with the ZIP load and the dynamic load models for all the transactions. It is found that the ATC values decrease in the presence of the dynamic loads for multilateral transactions T6 and T7.

To demonstrate the effectiveness of the proposed formulation in obtaining the Hopf bifurcation limit to determine the ATC, the results obtained with this formulation has been compared with those obtained using the formulation proposed in [14]. The ATC values have been obtained considering constant power type loads for the same transactions, as considered in [14]. Table V presents the details of the transactions considered. The ATC values, obtained using the two formulations, for the system intact case are compared in Table VI. It can be observed that the critical eigen values obtained with the proposed formulation has zero real part, whereas those obtained with the formulation given in [14] has small positive real part. The occurrence of this small positive real part may be due to the directional derivative of the objective function becoming very small, preventing the solution to move towards the optimal value. Thus, the proposed formulation is more effective in computing the Hopf bifurcation limit, as compared to that proposed in [14].

**Table IV: Dynamic ATC Values for Transaction T1 with Dynamic Load**

<table>
<thead>
<tr>
<th>Line Outage</th>
<th>( \lambda )</th>
<th>ATC (MW)</th>
<th>Critical eigen value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3.3537</td>
<td>376</td>
<td>0.0000±i2.8837</td>
</tr>
<tr>
<td>31-1</td>
<td>2.4372</td>
<td>224</td>
<td>0.0000±i2.5756</td>
</tr>
<tr>
<td>38-31</td>
<td>2.4381</td>
<td>227</td>
<td>0.0000±i2.5793</td>
</tr>
<tr>
<td>29-28</td>
<td>1.7868</td>
<td>124</td>
<td>0.0000±i3.0357</td>
</tr>
<tr>
<td>26-29</td>
<td>2.1706</td>
<td>184</td>
<td>0.0000±i3.0402</td>
</tr>
<tr>
<td>26-28</td>
<td>2.3926</td>
<td>204</td>
<td>0.0000±i3.0031</td>
</tr>
<tr>
<td>38-25</td>
<td>2.3891</td>
<td>203</td>
<td>0.0000±i2.7249</td>
</tr>
<tr>
<td>26-27</td>
<td>2.3892</td>
<td>219</td>
<td>0.0000±i2.8648</td>
</tr>
<tr>
<td>25-26</td>
<td>2.4634</td>
<td>231</td>
<td>0.0000±i2.9186</td>
</tr>
<tr>
<td>39-32</td>
<td>3.0554</td>
<td>324</td>
<td>0.0000±i2.7248</td>
</tr>
</tbody>
</table>

**Table V: Transaction Details for Comparison with Formulation Given in [14]**

<table>
<thead>
<tr>
<th>Transaction</th>
<th>Seller bus (Transaction share)</th>
<th>Buyer bus (Transaction share)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>9 (1.0)</td>
<td>32 (1.0)</td>
</tr>
<tr>
<td>T2</td>
<td>3 (1.0)</td>
<td>32 (1.0)</td>
</tr>
<tr>
<td>T3</td>
<td>1, 8 (0.6, 0.4)</td>
<td>32 (1.0)</td>
</tr>
<tr>
<td>T4</td>
<td>3, 10 (0.4, 0.6)</td>
<td>32 (1.0)</td>
</tr>
<tr>
<td>T5</td>
<td>1, 8 (0.5, 0.5)</td>
<td>32, 36 (0.5, 0.5)</td>
</tr>
<tr>
<td>T6</td>
<td>1, 3, 8 (0.4, 0.2, 0.4)</td>
<td>18,37 (0.5,0.5)</td>
</tr>
<tr>
<td>T7</td>
<td>1,3,8,10 (0.2,0.5,0.2,0.1)</td>
<td>18,26 (0.4,0.6)</td>
</tr>
</tbody>
</table>

**Table VI: Comparison of ATC Values with Formulation Given in [14]**

The ATC values are much lower as compared to that at the base case. The most credible contingency as shown in Table II for transaction T1 does not correspond to the minimum ATC value in Table III due to different transaction values in the two cases.
VI. CONCLUSION

A novel optimization based formulation has been proposed to determine the dynamic Available Transfer Capability (ATC), considering Hopf bifurcation limit, in an electricity market having bilateral as well as multilateral transactions. The optimization problem aims to maximize the scalar loading factor, while satisfying the Hopf bifurcation and power balance conditions. Only Hopf bifurcation limit has been used in this work. However other static constraints such as voltage limit, line flow limit, generator real and reactive power limit can also be easily included in the same formulation. An oscillatory stability based contingency screening index has been used to identify few critical contingencies to be considered in determining the ATC. The simulation results provide the following main conclusions:

- The contingency screening index filtered out the critical contingencies accurately. This can be inferred from the ATC values observed at the critical contingencies, which are much lower as compared to that at the base case.
- The proposed formulation is able to determine the oscillatory stability constrained ATC accurately, as confirmed by the pure imaginary critical eigen values obtained at the optimal value of the loading factor.
- The proposed formulation provides more accurate value of the ATC as compared to that based on minimizing real part of the eigen value, proposed in [14].
- The ATC values are found to decrease slightly, in most of the cases, in the presence of the dynamic loads in the system.

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