CHAPTER 2

AVAILABLE TRANSFER CAPABILITY DETERMINATION

2.1 INTRODUCTION

Deregulation of the electricity industry throughout the world aims at creating a competitive market to trade electricity, which generates a host of new technical challenges to market participants and power system researchers. Power system restructuring environment policies adopted in various developed countries and the structure followed in some of the developing countries are discussed in length by Rudnick (1996), Tabors (1996), Baji and Ashok (1998), Srivatsava and Shahidehpour (2002) and Sood et al (2002). For transmission systems, it requires non-discriminatory open access to transmission resources. Therefore, for better transmission services support and full utilization of transmission assets, one of the major challenges is to accurately gauge the transfer capability remaining in the system for further transactions which is termed the available transfer capability (ATC).

In order to have open access in the restructured power market, a transparent knowledge about the generation capacity and the transmission capability of the system has to be determined. Since many utilities provide transaction services for wholesale customers, they must know about the post information on ATC of their transmission networks. Such information will help power marketers, sellers and buyers in reserving transmission services. Various mathematical models have been developed by the researchers to determine the ATC of the transmission system and it has been discussed in

In this thesis, ATC is computed using PTDFs in CEED environment for IEEE test systems. Before computing the ATC, the basic optimal power flow solution has to be determined. Yurevich and Wong (1999) has validated evolutionary programming (EP) algorithm to solve optimal power flow problem with quadratic and sine component cost functions. Kulkarni et al (2000) has proposed a price penalty factor for solving the CEED problem, which blends the emission costs with the normal fuel costs. Venkatesh et al (2003) has applied evolutionary computational techniques for solving CEED problem with non-linear scaling factor and demonstrated on various IEEE test systems. CEED problem is formulated as a multi-objective problem by considering both economy and emission simultaneously. This bi-objective problem is converted into single objective function using price penalty approach.
With the introduction of competition in the utility industry, it is possible for customers to buy the less expensive electrical energy from remote location. Therefore, system operators face the need to monitor and coordinate power transactions taking place over long distances in different areas. Furthermore, in the case of multi-area system, ATC computations become more challenging owing to the reluctance of individual areas to share their operating information with each other. Different methods for the computation of multi-area total transfer capability are described in Shaaban et al (2003), Zhao and Abur (2004), Min et al (2005) and Min and Abur (2006). ATC can be evaluated from TTC after accounting for various margins. A novel approach for calculating multi-area ATC is presented in this thesis.

This work describes the evaluation of single area ATC using Power Transfer Distribution Factors (PTDFs) in Combined Economic Emission Dispatch (CEED) environment. In addition, a novel method for the determination of multi-area ATC in CEED environment with the inclusion of Participation Factors (PF) is proposed. Simultaneous bilateral and multilateral wheeling transactions have been carried out on IEEE 30 bus and IEEE 118 bus systems considered. Assessment of single and multi-area ATC for both normal, line and generator outage contingencies are presented. The obtained single and multi-area ATC results are compared with Power World Simulator package to justify its accuracy.

2.2 AVAILABLE TRANSFER CAPABILITY

Available Transfer Capability (ATC) is a measure of the transfer capability remaining in the physical transmission network for further commercial activity over and above the already committed uses as outlined in NERC Report (1996). Mathematically, ATC is defined as:
$ATC = TTC - TRM - \{ ETC + CBM \}$ \hspace{1cm} (2.1)

where, TTC is the Total Transfer Capability. Existing Transmission commitments (ETC) is the power flow over the transmission paths at the desired time at which ATC should be calculated. This is the already committed used power on the transmission path. The margins TRM and CBM are decided as per the relevant policies of the system operator and the market participants. TRM and CBM are to be accounted separately when such definition is used for ATC determination and this thesis utilizes sensitivity factors. In general, ATC is defined by,

$$ATC = TTC - ETC$$ \hspace{1cm} (2.2)

Utilities would have to determine adequately their ATC’s to insure that system reliability is maintained while serving a wide range of transmission transactions. ATC at base case, between bus $m$ and bus $n$ using line flow limit (thermal limit) criterion is mathematically formulated using PTDF as,

$$ATC_{mn} = \min \{ T_{ij,mn} \}, \; ij \in N_L$$ \hspace{1cm} (2.3)

where $T_{ij,mn}$ denotes the transfer limit values for each line in the system. It is given by,

$$T_{ij,mn} = \begin{cases} \frac{(P_{ij}^{\text{max}} - P_{ij}^0)}{PTDF_{ij,mn}} ; & PTDF_{ij,mn} > 0 \\ \alpha \text{ (infinite)} ; & PTDF_{ij,mn} = 0 \\ \frac{(-P_{ij}^{\text{max}} - P_{ij}^0)}{PTDF_{ij,mn}} ; & PTDF_{ij,mn} < 0 \end{cases}$$ \hspace{1cm} (2.4)

In this paper, the optimal settings of generators under CEED environment are considered as a base case power flow. The PTDF may be either DCPTDF or ACPTDF and it depends on the method of formulation.
The method of formulating PTDF is common for both single area and multi-area ATC evaluation and it is explained in section 2.4. For multi-area ATC calculation, in addition to PTDFs, PFs should also be included and it is explained in section 2.7.

2.3 CEED PROBLEM FORMULATION

Generally in the restructured environment, generator companies are responsible for the re-dispatch of power by considering the emissions according to their state laws and submit their bids to transmission system operator. System operator is responsible for calculating ATC before committing the transactions. But in most of the developing countries, the restructuring process of power industry is still in the infant stage. Still the structure is vertically integrated but they purchase power from Independent Power Producers (IPP) to meet the growing demand. Hence, the regional transmission operator is responsible for the re-dispatch of generator power by considering the physical limits of the system and emissions standards. There are power markets which support transactions based on OPF in addition to centralized dispatch based on bids. Therefore the proposed CEED based ATC calculation method can be well suited for such a scenario.

Optimization of CEED problem has been mathematically formulated and is given by the following equation:

$$
\phi = min \sum_{i=1}^{N} f_i(FC, EC)
$$

(2.5)

The cost is optimized within the following constraints. The power system constraint is given as follows,

$$
\sum_{i=1}^{N} P_{gi} = P_d + P_l
$$

(2.6)
The power flow equation of the power network:

\[ g(v, \vartheta) = 0 \]  \hspace{1cm} (2.7)

where

\[
g(V, \vartheta) = \begin{cases} 
- P_i(v, \vartheta) - P_{\text{net}}^i & \text{For each PQ bus } i \\
Q_i(v, \vartheta) - Q_{\text{net}}^i & \text{For each PV bus } m, \\
P_m(v, \vartheta) - P_{\text{net}}^m & \text{not including ref. bus}
\end{cases}
\]

The inequality constraint on real power generation of each generator \( i \):

\[ P_{gi}^{\text{min}} \leq P_{gi} \leq P_{gi}^{\text{max}} \]  \hspace{1cm} (2.8)

The inequality constraint on voltage of each PQ bus:

\[ V_{i}^{\text{min}} \leq V_{i} \leq V_{i}^{\text{max}} \]  \hspace{1cm} (2.9)

Power limit on transmission line is given by:

\[ S_{ij} \leq S_{ij}^{\text{max}} \]  \hspace{1cm} (2.10)

Total fuel cost of generation FC (US$/h) in terms of control variables of generator powers can expressed as,

\[ FC = \sum_{i=1}^{N_g} \left( a_i P_{gi}^2 + b_i P_{gi} + c_i \right) \]  \hspace{1cm} (2.11)

Total emission of generation EC (lb/h) can be expressed as,

\[ EC = \sum_{i=1}^{N_g} \left( \alpha_i P_{gi}^3 + \beta_i P_{gi} + \gamma_i \right) \]  \hspace{1cm} (2.12)
The bi-objective optimization problem (2.5) is converted into single optimization problem by introducing price penalty factor, $h$, as explained by Kulkarni et al (2000). It is given by,

$$\text{Minimize } \phi = (FC + h \cdot EC)$$  \hspace{1cm} (2.13)

CEED optimization problem is solved using evolutionary programming subject to the constraints given by equations (2.6)-(2.10). The price penalty factor $h$ blends the emission with fuel cost. The price penalty factor $h_i$ is the ratio between the maximum fuel cost and maximum emission of corresponding generator,

$$h_i = \frac{FC(P_{\text{max}})}{EC(P_{\text{max}})} \text{ $/lb} \quad i=1,2,\ldots,N_g$$  \hspace{1cm} (2.14)

The procedural steps as given by Venkatesh et al (2003) are to be followed to find the price penalty factor for a particular load demand and also to obtain the optimal settings of the generators of the IEEE test systems considered.

### 2.4 PTDF DETERMINATION

PTDFs determine the linear impact of a transfer (or changes in power injection) on the elements of the power system. These values provide a linearized approximation of how the flow on the transmission lines and interfaces change in response to transaction between the seller and buyer. For single area ATC, the transaction will be between seller bus and buyer bus present in the area and for multi-area ATC, the transaction will be between two areas.
2.4.1 DCPTDF Formulation

The linear DC Power Transfer Distribution Factors (DCPTDF) is used to allocate MW flows on the lines for a transaction in the system and they are based on DC power flow equations. These equations are simply the real part of decoupled power flow equations in which voltages and reactive powers are ignored and only angle and real powers are solved by iterating

\[ [\Delta \delta] = [B]^{-1} \Delta P \]  

(2.15)

Then, change in power due to transaction between bus \( m \) and bus \( n \) is determined. Similarly the change in angle due to the above transaction i.e., \( \Delta \delta_{mn} \) is calculated. The net change in angle is

\[ \Delta \delta = \Delta \delta^0 - \Delta \delta_{mn} \]  

(2.16)

The power flow on line \( i \) and \( j \) is given by

\[ P_{ij, mn} = \left( \frac{1}{x_{ij}} \right) (\Delta \delta_i - \Delta \delta_j) \]  

(2.17)

Thereafter, PTDF is calculated as explained in the proceeding section. However, this has a poor accuracy due to assumption involved in the DC power flow model and it has been pointed out by Christie et al (2000).

2.4.2 ACPTDF Formulation

The AC power transfer distribution factors presented and discussed by Weber (2000), Kumar and Srivatsava (2002) and Kumar et al (2004) for the calculation of ATC has been used to find various transmission system quantities for a change in MW transaction at different operating conditions.
Consider a bilateral transaction $t_k$ between a seller bus $m$ and buyer bus $n$. Line $l$ carries the part of the transacted power and is connected between buses $i$ and $j$. For a change in real power transaction among the above buyer and seller by $\Delta t_k$ MW, if the change in a transmission line quantity $q_1$ is $\Delta q_1$, power transfer distribution factors can be defined as,

$$PTDF_{ij,mn} = \frac{\Delta q_1}{\Delta t_k}$$ \hfill (2.18)

The transmission quantity $q_l$ can be either real power flow from bus $i$ to $j$ ($P_{ij}$) (or) real power flow from bus $j$ to bus $i$ ($P_{ji}$). The above factors have been proposed to compute at a base case load flow with results using sensitivity properties of NRLF Jacobian. Consider full Jacobian in polar coordinates $[J_T^T]$, defined to include all the buses except slack (including $\Delta Q$-$\Delta V$ equations also for $PV$ buses).

$$\begin{bmatrix} \Delta \delta \\Delta V \end{bmatrix} = \begin{bmatrix} \frac{\hat{c}P}{\hat{c}\delta} & \frac{\hat{c}P}{\hat{c}V} \end{bmatrix}^{-1} \begin{bmatrix} \frac{\hat{c}P}{\hat{c}Q} & \frac{\hat{c}Q}{\hat{c}V} \end{bmatrix} \begin{bmatrix} \Delta P \\Delta Q \end{bmatrix} = [J_T^T]^T \begin{bmatrix} \Delta P \\Delta Q \end{bmatrix}$$ \hfill (2.19)

In equation (2.19), the change in active power flow of line $i - j$ with respect to changes in state variables is determined as,

$$\frac{\hat{c}P_y}{\hat{c}\delta_e} = \begin{cases} 0 & \text{for } e \neq i, j \\ -V_i Y_y \sin(\delta_i - \delta_j - \theta_y) & \text{for } e = i \\ V_i Y_y \sin(\delta_i - \delta_j - \theta_y) & \text{for } e = j \end{cases}$$

$$\frac{\hat{c}P_y}{\hat{c}V_e} = \begin{cases} 0 & \text{for } e \neq i, j \\ 2V_i Y_y \cos \theta_y + V_j Y_y \cos(\delta_i - \delta_j - \theta_y) & \text{for } e = i \\ V_j Y_y \cos(\delta_i - \delta_j - \theta_y) & \text{for } e = j \end{cases}$$
In a base case load flow, if only one of the \( k^{th} \) bilateral transactions is changed by \( \Delta t_k \) MW, only the following two entries in the mismatch vector on right hand side of (2.19) will be non zero.

\[
\Delta P_i = \Delta t_k \quad \Delta P_j = -\Delta t_k
\]  

(2.20)

With the above mismatch vector elements, the change in voltage angle and magnitude at all buses can be computed from (2.19) and (2.20) and, hence, the new voltage profile can be calculated. These can be utilized to compute all the transmission quantities \( q_i \) and hence the corresponding in these quantities \( q_i \) from the base case. Once the \( q_i \) for all the lines corresponding to a change in transaction \( t_k \) is known, PTDFs can be obtained from (2.18). These ACPTDFs, which are computed at a base load flow condition, have been utilized for computing change in transmission quantities at other operating conditions as well.

ACPTDF is also calculated for multilateral transaction in which group of sellers have a bilateral contract with group of buyers. The change in multilateral transaction can be assumed to be shared equally by each of the sellers and buyers. However, the transaction amount can be shared in any pre-decided ratio in a deregulated environment. The mismatch vector for the multilateral transactions will have non zero entries corresponding to the buyer and seller buses. The rest of the procedure for calculation of ACPTDF will be the same as outlined above the bilateral transaction case.

2.5 OTDF FORMULATION FOR LINE OUTAGE CONTINGENCIES

Line Outage Power Transfer Distribution Factor (LOPTDF) is a sensitivity measure of how a change in a line’s status affects the flows on other lines in the system. When calculating PTDF values for interfaces that
include contingent lines, the PTDF values calculated are actually called as an Outage Transfer Distribution Factor (OTDF). An OTDF is similar to PTDF, expect and OTDF provides a linearized approximation of the post-outage change in flow on a transmission line in response to a transaction between the seller and buyer. The OTDF value is a function of PTDF values and LOPTDF values.

Consider the outage of a line connected between buses \( r \) and \( s \) having pre outage real power flow \( P_{rs}^o \) and \( P_{sr}^o \) from bus \( r \) to bus \( s \) and bus \( s \) to bus \( r \) respectively. Let \( P_{ij, rs} \) be the post outage flow in a line connected between buses \( i \) and \( j \). The change in the line flows can be written as,

\[
\Delta P_{ij, rs} = P_{ij, rs} - P_{ij, rs}^o
\]  

(2.21)

The Line Outage Power Transfer Distribution Factor (LOPTDF) can be defined as the ratio of \( P_{ij, rs} \) to the real power flow transmitted in the line taken for outage and connected between the buses \( r \) and \( s \).

\[
LOPTDF_{ij, rs} = \frac{\Delta P_{ij, rs}}{P_{rs}^o}
\]  

(2.22)

The OTDF value for line \( i-j \) during outage of line \( r-s \) is

\[
OTDF_{ij, rs} = PTDF_{ij, mn} + LOPTDF_{ij, rs} \times PTDF_{rs, mn}
\]  

(2.23)

Then, for each line during each contingency, determine another transfer limit value

\[
T_{ij, rs} = \begin{cases} 
\frac{P_{ij}^\text{max} - P_{ij, rs}}{OTDF_{ij, rs}} & ; \quad OTDF_{ij, rs} > 0 \\
\alpha \text{ (infinite)} & ; \quad OTDF_{ij, rs} = 0 \\
\frac{-P_{ij}^\text{max} - P_{ij, rs}}{OTDF_{ij, rs}} & ; \quad OTDF_{ij, rs} < 0 
\end{cases}
\]  

(2.24)
ATC under a line outage condition, for the transaction between \( m \) and \( n \), taking the line flow limit criteria into account can be determined as

\[
ATC_{mn,rs} = \min \{T_{ij,sw} T_{ij,rs}\}, \quad ij \in N_L \quad \text{and} \quad rs \in N_{LC}
\] (2.25)

The contingent line is selected based on real power line flow Performance Index (PI) as explained by Ejebe and Wollenberg (1979). The severity of the system loading under normal and contingency cases in an area or between areas can be described by a PI value as given below,

\[
PI = \sum_{i=1}^{N_L} \sum_{j=1}^{N_L} W_{ij} \left[ \frac{P_{ij}}{P_{ij}^{\max}} \right]^{2n}
\] (2.26)

PI will be small when all the lines are within their limits and reach a high value when there are overloads.

2.6 GODF FORMULATION FOR GENERATOR OUTAGE CONTINGENCIES

The outage of generator is equivalent to a transfer of \(-P_k^0\) from the generator bus to the contingency assumed sink. Hence it is correct to assume that GODF’s are equal to PTDF’s of this transfer. For DC power flow method, generation shift sensitivity factor \( a_{ij,k} \) are calculated and denotes the sensitivity of the MW power flow on line \( i-j \) to a change or outage of generation occurring at bus \( k \).

It is assumed that, the change in generation, \( \Delta P_k \) is exactly compensated by an opposite change in generation at the reference bus, and that all other generators remain fixed. Using the pre-calculated set of ‘a’ factors, the change in power flow on each line due to the generator outage is given by,
\[ \Delta P_{ij,k} = a_{ij,k} \times \Delta P_k \]  

(2.27)

where \( \Delta P_k = -P_k^0 \) and the outage generator was generating \( P_k^0 \) before outage. The resultant power flow on line \( i-j \) due to generator outage at bus \( k \) is given by,

\[ P_{ij,k} = P_{ij}^0 + \Delta P_{ij,k}, \quad ij \in N_L \quad \text{and} \quad k \in N_{GC} \]  

(2.28)

For AC power flow method, the network sensitivity methods may not be adequate and the operation of control system will have to incorporate full AC power flow for each generator outage contingency analysis.

For each generator outage contingency determine transfer limit value as,

\[
T_{ij,k} = \begin{cases} 
\frac{(P_{ij}^{\max} - P_{ij,k})}{GODF_{ij,k}} ; & GODF_{ij,k} > 0 \\
\alpha \text{ (infinite)} ; & GODF_{ij,k} = 0 \\
\frac{(-P_{ij}^{\max} - P_{ij,k})}{GODF_{ij,k}} ; & GODF_{ij,k} < 0
\end{cases}
\]  

(2.29)

ATC under generator outage condition, for the transaction between \( m \) and \( n \), taking the line flow limit criteria into account can be determined as

\[ ATC_{mn,k} = \min \{T_{ij,mn}, T_{ij,k} \}, \quad ij \in N_L \quad \text{and} \quad k \in N_{GC} \]  

(2.30)

2.7 PF FOR MULTI-AREA ATC DETERMINATION

As the size of the system grow due to the consolidation of different control areas under a common grid coordinator, calculation of ATC becomes more challenging. It requires collection of network data from all control areas and solving a very large scale power flow problem considering all limits in all
areas. Shaaban et al (2003) has demonstrated the usage of Bender’s decomposition method to calculate multi-area ATC. The base case security constraints are considered in the master problem and the contingencies are handled as a series of sub-problems. Zhao and Abur (2004) has presented a two level multi-area coordinator solution approach for calculating total transfer capability using PTDFs. Min et al (2005) has described a method in which a quadratic approximation of non-linear PTDFs is developed first using Taylor series expansion. Then the non-linear PTDFs have been properly updated to calculate TTC for multi-area. Min and Abur (2006) has come out with the method of solving multi-area TTC problem by using a network decomposition approach based on REI-type network equivalents. Each area uses REI equivalents of external areas to compute its TTC via the continuation power flow (CPF). ATC can be derived from TTC by discounting appropriate quantities accounting for various commitments and margins.

In this thesis, a new non-iterative approach is presented using Participation Factors in addition to power transfer distribution factors. For the purpose of calculating ATC, buyer and seller transactors are to be specified. This can be slack, a single bus, injection groups, areas etc. When multiple generators exist in the transactor, such as the case of areas or injection groups, participation factors need to be assigned. By default, those participation factors of generators in the areas are used and the modeling of participation factors depends on the actual purpose of determining multi-area ATC. Typical cases are,

(i) For planning study i.e., Transactions from a set of less cheap generators in any area to all the system loads in another area, then the PF of generation can be proportional to cost or
generator reserve margin. PF of loads could be proportional to MW load.

(ii) For power transfer i.e., Transfer of additional import to a control area from another control area. In this case, generation in one area increases while generation in another area decreases. PF of both areas are set proportional to reserve margin or cost.

An area control will become the limiter if the generator limits are reached and therefore there must be enough generating reserve. For the transaction taking place between two areas i.e. one is seller area and the other is buyer area, the formulation of multi-area ATC problem is as follows:

For each generator inside the area, the actual participation factor used is

\[ PF_i = \frac{Gen_i}{\sum (All\;Gen,\;in\;an\;area)} \]  \hspace{1cm} (2.31)

Assuming that the inverse of Jacobian i.e., \([J_T]^T\) is \([S_T]\), equation (2.19) can be written as,

\[
\begin{bmatrix}
\Delta \delta \\
\Delta V
\end{bmatrix} = [S_T] \begin{bmatrix}
\Delta P \\
\Delta Q
\end{bmatrix}
\]  \hspace{1cm} (2.32)

In the above equation, \(\Delta P_k = 0\) and \(\Delta Q_k = 0\) where \(k = 1, \ldots, h, k \neq i, j\). In the transaction matrix for seller area, in the place of generators, participation factor (PF) value assigned is,

\[ \Delta P_{S_i} + PF_i \hspace{0.5cm} \text{Subject to} \hspace{0.5cm} \sum_{i=1}^{n} PF_i = 1 \]  \hspace{1cm} (2.33)
and in the transaction matrix for buyer area, in the place of generators, the PF value assigned is,

\[ \Delta P_{B_i} - PF_j \quad \text{Subject to} \quad \sum_{j=1}^{n} PF_j = 1 \quad (2.34) \]

where \( n \) = number of generators in buyer and seller areas. All other entries in the buyer and seller area transaction matrices other than \( \Delta P_{S_i} \) and \( \Delta P_{B_j} \) are zeros. The change in voltage angle and magnitude at all buses present in the areas are calculated and hence the new voltage profile can be determined. Area wise PTDF is simply a function of these voltages and angle sensitivities and thereafter the calculation of multi-area ATC for normal and contingency mode are similar to the procedure presented for single area ATC determination.

### 2.8 ALGORITHM

The basic steps used for computing ATC and Multi-area ATC for each transaction are as follows:

- **Step 1:** Read the system input data.
- **Step 2:** Run a base case load flow in CEED environment and determine the optimal settings of the generators as explained by Venkatesh et al (2003).
- **Step 3:** Consider wheeling transactions \( (t_k) \).
- **Step 4:** Compute AC power transfer distribution factors as per equation (2.18).
- **Step 5:** Take transactions as variables, line flow, and real and reactive power limits of generators as constraints and compute the feasible wheeling transactions.
Step 6: Dispatch the possible transactions and determine the ATC as per equation (2.3).

Step 7: Check if any line outage contingency analysis is to be performed. If so, select contingent line as per equation (2.26) and then proceed, otherwise go to step 12.

Step 8: Calculate LOPTDF and OTDF as per equations (2.22) and (2.23)

Step 9: Calculate ATC for line outage contingency case as per equation (2.25)

Step 10: Check if any generator outage contingency analysis is to be performed. If so, determine GODF as per the procedure outlined, otherwise go to step 12

Step 11: Calculate ATC for generator outage contingency using GODF case as per equation (2.30)

Step 12: Is any other transaction has to be carried out, then consider the next transaction and go to step 4, otherwise, proceed.

Step 13: Print the value ATC.

For the purpose of computing multi-area ATC, the integrated system is formulated into a multi-area system and suitable participation factors are assigned for generators present in each area as per equation (2.31). Then corresponding changes are made to the transaction matrices for seller and buyer areas as per equations (2.33) and (2.34). And thereafter, the procedure for calculation of area wise PTDF and multi-area ATC are similar to the steps presented in the algorithm.
2.9 POWER WORLD SIMULATOR - AN OVERVIEW

Power World Simulator is a power system simulation package designed from the ground up to be user-friendly and highly interactive. Simulator has the power for serious engineering analysis, but it is also so interactive and graphical that it can be used to explain power system operations to non-technical audiences. At its core is a comprehensive, robust power flow solution engine capable of efficiently solving systems of up to 100,000 buses. Simulator’s extensive use of graphics and animation greatly increases the user’s understanding of system characteristics, problems, and constraints, as well as of how to remedy them. This package also contains various tools and add-on tools. More information can be obtained from the web site http://www.powerworld.com.

2.10 SIMULATION RESULTS AND DISCUSSIONS

Single and multi-area are considered appropriately for the test systems. Single area ATC determination is carried out for the simultaneous bilateral and multilateral transactions. Area wise transactions are considered for multi-area ATC determination. The assessment of ATC has been illustrated on IEEE 30 bus and IEEE 118 bus systems by considering single and multi-area for normal mode operation, line and generator outage contingency mode operation under restructured environment. The proposed method is well suited for developing countries. For demonstration, as followed in many related literatures, IEEE test systems are used. Thermal limit of each line is considered as a constraint and reactive power demand at load buses has been taken as constant. In the ATC determination, generator settings are obtained from CEED environment. The simulation studies are carried out on Intel Pentium IV, 2.66 GHz system in MATLAB environment. The results are compared with Power World Simulator (PWS) package. The limiting elements are also given for each transaction. Some of the results are not possible to verify because of the limitation of PWS package. (For example
multilateral transactions are not possible to perform using Power World Simulator).

### 2.10.1 Single Area ATC Calculation

The system details for IEEE 30 and IEEE 118 bus system are taken from http://www.ee.washington.edu/research/pstca. It is also presented in Appendix 2 and 3. CEED base case values of the generators of the test systems are obtained as explained by Venkatesh et al (2003). The transactions which provide better ATC values are considered. In IEEE 30 bus system, two simultaneous bilateral transactions $T_1$ (2-28) and $T_2$ (5-23) and a multilateral transaction $T_3$ (2, 11 - 28, 26) are considered and the results are given in Table 2.1.

Limiting elements are also found out for the considered transactions. Thermal limits of all limiting lines are given in Tables A2.2 and A4.2. For this IEEE 30 bus system, for all the transactions considered separately, DCPTDF, ACPTDF and PWS tool identified the same limiting line. In IEEE 118 bus system, three simultaneous bilateral transactions $T_1$ (1-118), $T_2$ (46-80) and $T_3$ (49-100) and a multilateral transaction $T_4$ (25, 59, 46 - 89, 100, 103, 111) are considered and the results are given in Table 2.2. For this test system, except for the multilateral transaction $T_3$, limiting element identified by the ACPTDF and PWS tool is same and it is different from the limiting element found out by DCPTDF method. For both the test systems, the ATC calculations are carried out in normal mode operation (case A) and (n-1) line contingency mode operation (case B). For line outage contingency mode operation, as per (2.26) outage of line 9-10 is considered for IEEE 30 bus system and outage of line 69-77 is considered for IEEE 118 bus system.

ACPTDF method is giving accurate ATC value compared to DCPTDF method. The validity of the results is also verified using PWS package. By comparing with PWS package, a small deviation in the ATC results using ACPTDF is found since the linearized AC method is not used for ATC determination.
### Table 2.1 ATC in MW for IEEE 30 bus system

<table>
<thead>
<tr>
<th>Transaction</th>
<th>Case</th>
<th>DCPTDF method</th>
<th>With PWS package</th>
<th>Limiting Element for DCPTDF</th>
<th>ACPTDF method</th>
<th>With PWS package</th>
<th>LOPTDF method</th>
<th>With PWS package</th>
<th>Limiting Element for ACPTDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>T₁ (2-28)</td>
<td>A</td>
<td>23.65</td>
<td>23.78</td>
<td>6 – 28</td>
<td>24.82</td>
<td>24.87</td>
<td>-</td>
<td>-</td>
<td>6 – 28</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>18.26</td>
<td>18.04</td>
<td></td>
<td>-</td>
<td>-</td>
<td>18.83</td>
<td>18.34</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>12.16</td>
<td>13.53</td>
<td></td>
<td>-</td>
<td>-</td>
<td>14.18</td>
<td>12.25</td>
<td></td>
</tr>
<tr>
<td>T₃(2, 11-28, 26)</td>
<td>A</td>
<td>15.56</td>
<td>-</td>
<td>6 – 28</td>
<td>16.95</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>6 – 28</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>11.35</td>
<td>-</td>
<td></td>
<td>-</td>
<td>-</td>
<td>12.23</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

Case A  - Normal mode operation
Case B  - Line outage contingency mode operation i.e., outage of line (9-10)
### Table 2.2 ATC in MW for IEEE 118 bus system

<table>
<thead>
<tr>
<th>Transaction</th>
<th>Case</th>
<th>DCPTDF method</th>
<th>With PWS package</th>
<th>Limiting Element for DCPTDF</th>
<th>ACPTDF method</th>
<th>With PWS package</th>
<th>LOPTDF method</th>
<th>With PWS package</th>
<th>Limiting Element for ACPTDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>T₁(1-118)</td>
<td>A</td>
<td>216.20</td>
<td>216.96</td>
<td>8 – 13</td>
<td>214.48</td>
<td>212.34</td>
<td>-</td>
<td>-</td>
<td>75 – 118</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>211.82</td>
<td>212.29</td>
<td></td>
<td>-</td>
<td>-</td>
<td>194.78</td>
<td>193.11</td>
<td></td>
</tr>
<tr>
<td>T₂(46-80)</td>
<td>A</td>
<td>425.22</td>
<td>426.54</td>
<td>68 – 81</td>
<td>363.42</td>
<td>360.45</td>
<td>-</td>
<td>-</td>
<td>81 – 80</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>303.76</td>
<td>305.52</td>
<td></td>
<td>-</td>
<td>-</td>
<td>245.41</td>
<td>243.41</td>
<td></td>
</tr>
<tr>
<td>T₃(49-100)</td>
<td>A</td>
<td>440.68</td>
<td>442.14</td>
<td>68 – 81</td>
<td>395.37</td>
<td>393.03</td>
<td>-</td>
<td>-</td>
<td>81 – 80</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>308.54</td>
<td>310.62</td>
<td></td>
<td>-</td>
<td>-</td>
<td>256.47</td>
<td>254.20</td>
<td></td>
</tr>
<tr>
<td>T₄(25, 59, 46 - 89, 100, 103, 111)</td>
<td>A</td>
<td>42.39</td>
<td>-</td>
<td>100 – 103</td>
<td>51.07</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>100 – 103</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>12.46</td>
<td>-</td>
<td></td>
<td>-</td>
<td>-</td>
<td>14.79</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

Case A  -  Normal mode operation  
Case B  -  Line outage contingency mode operation i.e., outage of line (69-77)
The ATC values obtained for contingency case are lesser than the base case. The limiting element of the transactions for the contingency case is found to be same with PWS package. In the case of contingency studies, LOPTDF method is more suitable than ACPTDF method for all transactions.

### 2.10.2 Multi-Area ATC Calculation

In the multi-area ATC calculation, two areas are considered in IEEE 30 bus system and three areas are considered in IEEE 118 bus system. The tie-lines present between two areas and areawise line of separation for IEEE 30 bus system using PWS package is shown in Figure 2.1. This Figure drawn using PWS package clearly depicts that the generators 8, 11 and 13 are present in Area 2 and all remaining generators in Area 1. Transaction is carried out between Area 1 and Area 2. For IEEE 118 bus system, tie-lines existing between three areas are shown in Figure 2.2. The generators and buses allocation for each area is presented in Table 2.3. Area boundaries are divided as described in Yong Fu et al (2005).

<table>
<thead>
<tr>
<th>Area / Generators</th>
<th>Area / Buses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area 1 10, 12, 25, 26, 31</td>
<td>Area 2 46, 49, 54, 59, 61, 65, 66, 69, 80</td>
</tr>
<tr>
<td>Area 1 1-23, 25-35, 70-75, 113-115, 117</td>
<td>Area 2 33-69, 76-81, 97-99, 116, 118</td>
</tr>
</tbody>
</table>

For IEEE 118 bus system, transactions are carried out between Area 1- Area 2, Area 1-Area 3 and Area 2- Area 3. The results obtained are compared with PWS package in order to justify the accuracy of the method proposed. The multi-area ATC calculation is carried out in both normal mode operation (Case A) and in (n-1) line outage contingency mode operation (case B).
Figure 2.1 Multi-area representation – IEEE 30 Bus system
Multi-area ATC results for the two test systems are given in Table 2.4. Similar to single area ATC, ACPTDF method is giving accurate ATC value compared to DCPTDF method. The limiting element of the transactions is found to be same with PWS package.

Figure 2.2 Tie-lines between areas – IEEE 118 Bus system

The multi-area ATC using ACPTDF for all of the areawise transactions are shown separately in Figure 2.3. The obtained ATC value is very high for transaction T₃ compared to other transactions since excess generation is available in Area 2. The difference between base case and contingency for transaction T₃ is high due to the fact that the line outage contingency (line 69-77) is present in Area 2. It is found that if the contingency element is present in the seller area then the difference in the ATC value is found to be large.
Table 2.4 Multi-Area ATC in MW for Two IEEE Test systems

<table>
<thead>
<tr>
<th>Test System</th>
<th>Transaction Case</th>
<th>DCPTDF method</th>
<th>With PWS package</th>
<th>Limiting Element for DCPTDF</th>
<th>ACPTDF method</th>
<th>With PWS package</th>
<th>LOPTDF method</th>
<th>With PWS package</th>
<th>Limiting Element for ACPTDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEEE 30 bus system</td>
<td>$T_1$(Area1-Area2) A</td>
<td>97.68</td>
<td>97.10</td>
<td>12 – 13</td>
<td>92.61</td>
<td>92.29</td>
<td>-</td>
<td>-</td>
<td>12 – 13</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>89.13</td>
<td>88.22</td>
<td>16 – 17</td>
<td>-</td>
<td>-</td>
<td>63.43</td>
<td>65.87</td>
<td>16 – 17</td>
</tr>
<tr>
<td>IEEE 118 bus system</td>
<td>$T_1$(Area1-Area2) A</td>
<td>342.31</td>
<td>344.41</td>
<td>8 – 30</td>
<td>379.20</td>
<td>385.83</td>
<td>-</td>
<td>-</td>
<td>8 – 30</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>341.42</td>
<td>344.36</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>377.08</td>
<td>380.75</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$T_2$(Area1-Area3) A</td>
<td>345.28</td>
<td>344.76</td>
<td>8 – 30</td>
<td>379.384</td>
<td>385.99</td>
<td>-</td>
<td>-</td>
<td>8 – 30</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>332.78</td>
<td>331.62</td>
<td>68 – 81</td>
<td>-</td>
<td>-</td>
<td>280.40</td>
<td>279.02</td>
<td>68 – 81</td>
</tr>
<tr>
<td></td>
<td>$T_3$(Area2-Area3) A</td>
<td>586.73</td>
<td>587.17</td>
<td>68 – 81</td>
<td>559.08</td>
<td>558.31</td>
<td>-</td>
<td>-</td>
<td>81 - 80</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>394.70</td>
<td>398.42</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>357.08</td>
<td>361.69</td>
<td></td>
</tr>
</tbody>
</table>

Case A - Normal mode operation
Case B - Line outage contingency mode operation i.e., outage of line (9-10) for IEEE 30 bus system and Outage of line (69-77) for IEEE 118 bus system
Figure 2.3 Multi-area ATC using ACPTDF for IEEE 118 Bus System

More generators are available in each area of IEEE 118 bus system and hence generator outage contingency is also carried out using AC Power flow for transactions between bus 66- bus 25, bus 103- bus 59, Area 2- Area 1, Area 3-Area 1 and Area 3- Area 2. ATC values are determined for both normal mode operation (Case C) and generator outage contingency cases. Outage of generator 12 in Area 1 (Case D) and outage of generator 65 in Area 2 (Case E) are considered. The ATC results for both bus to bus and area wise transactions are shown in Figure 2.4. Since excess generation is available in Area 2, the base case ATC values are higher for transaction Area 2 – Area 1 and bus 66 – bus 25 transactions compared to other transactions. The difference in ATC value between base case and the contingencies considered are very less for transactions between bus 66 – bus 25 and Area 2 – Area 1. It is because, the slack generator is available in Area 2 and hence it takes care of generations for the transactions. The execution time for the determination of ATC for IEEE 30 bus and IEEE 118 bus systems are found to be 7.829 seconds and 222.109 seconds respectively.
In this work, single area ATC determination using PTDF has been tested on two IEEE test systems with simultaneous bilateral and multilateral wheeling transactions. Also, multi-area ATC has been evaluated for both IEEE test systems with the novel method proposed. The obtained results are compared with Power World Simulator to justify the effectiveness and accuracy of the method. Line outage and Generator outage contingencies are also considered. For the various cases considered, the ATC determination using ACPTDF for the base case, LOPTDF for the line outage contingency and GODF for the generator outage contingency are found to be more accurate. The results obtained are found to be useful in determining the magnitude of feasible wheeling transactions under combined economic emission environment.

Figure 2.4  ATC with generator outage contingencies - IEEE118 Bus System

2.11  SUMMARY